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FURTHER INVESTIGATIONS OF THE EFFECT OF PRIOR CREEP ON MECHANICAL PROPERTIES OF C110M TITANIUM WITH EMPHASIS ON THE BAUSCHINGER EFFECT

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FOREWORD

This report was prepared by the University of Michigan Research Institute under USAF Contract No. AF 33(616)-3368. This contract was conducted under Project 7360, "Materials Analysis and Evaluation Techniques," Task 73604, "Fatigue and Creep of Materials." The work was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Lt. W. H. Hill acting as project engineer.

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ABSTRACT

A study of the effect of prior creep at 650° to 800°F on the short-time mechanical properties of C110M sheet showed property changes characteristic of the Bauschinger effect. After creep in tension, the tensile yield strength was increased and the compressive yield strength was decreased.

Creep-exposure at 700°F was found to cause Bauschinger effects almost as large as those reported in the literature for cold-stretching. The magnitude of the effect depended to some extent on the direction of the applied stress with respect to the rolling direction of the sheet, possibly due to a Bauschinger effect present in the original sheet as well as preferred orientation effects. The time of creep-exposure also governed the extent of the effect. A study of variable strain paths indicated that there was no apparent difference between the effects of short-time plastic strain and creep strain in inducing a Bauschinger effect. However, for a given deformation, recovery effects caused a reduction in the effect as the creep time or temperature was increased. Periods of exposure at no load at 700°F were found to be effective in removing the Bauschinger effect.

The test material was also found to be subject to a structural instability during testing which accounted for increased strength and decreased ductility. The instability was a stress-activated breakdown of non-equilibrium beta to form a secondary alpha phase. Strain hardening during testing was at most a minor factor.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. J. Trapp
Chief, Strength and Dynamics Branch
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INTRODUCTION

The effect of elevated temperature creep-exposure on the short-time mechanical properties of aircraft structual metals has been the subject of an investigation conducted at the University of Michigan for the past three years under the sponsorship of the Materials Laboratory, Wright Air Development Center, U. S. Air Force, under Contract AF 33(616)-3368. The materials studied included C110M titanium (Ref. 1), 2024-T86 aluminum (Ref. 2), 17-7PH stainless steel in the TH1050 condition (Ref. 3) and RH950 condition (Ref. 4) and Ti-16-2.5Al titanium alloy (Ref. 5).

The research has had the objective of accumulating the background information required to gain an insight into the basic principles governing creep damage to mechanical properties. Due to the absence of background information on this subject, systematic surveys of the effects of representative creep-exposures on both the room temperature properties and the properties at the exposure temperature have been necessary. The exposures have generally been conducted at three temperatures in the normally useful range of the material inquestion---these temperatures were 650°, 700° and 800°F in the case of C110M. The exposure times were limited to 10, 50 or 100 hours, while the range of creep deformations studied was normally zero to 2 percent.

For the C110M alloy it was previously shown (Ref. 1) that creep-exposure in tension tended to raise the short-time tensile yield strength and decrease the compressive yield strength---a behavior consistent with the definition of the Bauschinger effect, "the phenomenon by which plastic deformation of a metal raises the yield strength in the direction of plastic flow and decreases the yield strength in the opposite direction." (Ref. 6)

The present report extends the work of Reference 1 by detailed study of some aspects of the Bauschinger effect. In addition to re-evaluating previous data and surveying the theoretical basis for the Bauschinger effect, additional research was conducted on the effect of variable strain paths at 700°F, and the dependence of the effect on specimen orientation. Also included was a study of metallographic changes occurring during creep-exposure.

TEST MATERIAL

Eleven sheets of C110M titanium alloy in the annealed condition were received from the Rem-Cru Titanium Corporation in October of 1956. The material was all from Heat A1172600. The sheets were 0.064 inches thick by 30-36 inches wide by 60-90 inches long. The certified chemical analysis furnished by the producer follows:

Element	Percent (weight)
Manganese	7.9
Carbon	0.10
Nitrogen	0.02
Hydrogen	0.0093

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The manufacturer's reported properties for this material were the following:

Ultimate Tensile Strength	149,400 psi
Tensile Yield Strength	147,200 psi
Elongation	15.0 percent
Bend	3T

TEST SPECIMENS

Of the eleven sheets of C110M received, four were arbitrarily selected for providing test specimens. The longitudinal test specimens were chosen from among the first three sheets to provide a measure of the variation in properties between sheets and within individual sheets. The fourth sheet was used for studies of various specimen orientations and its sampling is discussed elsewhere (page 15).

The longitudinal sampling procedure adopted was designed to permit economical utilization of the material. The sampling scheme for an individual sheet is illustrated in Figure 1. Each sheet was divided into one-inch wide strips running the length of the sheet. Over the 90-inch length of the sheet four sections or quarters of length were laid out. One end of the sheet was arbitrarily designated the "A" end and its subsections labeled AA and AB, while the other end was designated the "C" end and its subsections labeled CC and CD. Occasionally the AA samples were merely labeled A and the CC samples labeled C. The individual specimens were stamped with a number sequence designating the sheet number, section number, and the strip number. Thus, the specimen labeled 2CD-17T is a tensile specimen from the CD end of strip 17 from Sheet 2.

The details of the test specimens used in this investigation are shown in Figure 2. All specimens for the tests of mechanical properties were designed so that they could be machined from the creep specimens following the desired exposure. For exposure to creep, the width of the gage section of the specimens was machined 0.030 inches over the 0.5 inch nominal width. This was machined off after creep exposure. This procedure permitted the measurement of the properties of the material itself unaffected by the particular edge effects, if any, associated with the exposure of the specimen.

For ease in machining, jigs were constructed so that five or six specimens could be made concurrently. The blanks were milled to rough dimensions and the shoulder radii and gage sections were then ground to the finished dimensions.

TEST EQUIPMENT AND PROCEDURES

Detailed discussion of the development of the test equipment and procedures has been previously given (Refs. 2 and 3) and will not be repeated in the present report. Wherever applicable, ASTM Recommend Practices were adhered to in test procedures.

The creep-exposure tests were carried out in individual creep-testing machines with heating provided by a wire wound resistance furnace fitting over the specimen assembly. Strain measurements were accomplished using a modified Martens optical extensometer system. All creep-exposure specimens were placed in the hot furnace at about 50°F below the desired test temperature. The specimens were then brought up to temperature and distribution in a standard four-hour "hot load" period and then the stress was applied.

Tensile and compression tests were conducted in a Baldwin-Southwark hydraulic tensile machine equipped with a strain pacer to give a strain rate of 0.005 inches per inch per minute. A recording extensometer system employing a micro-former strain gage was used to give a continuous plot of the test results. The 0.2-percent offset yield strength was determined for all tension and compression tests. A special compression testing fixture which included a loading ram and guide blocks to restrain lateral buckling of the specimen was used.

Specimens prepared for optical or electron microscope examination were mounted in bakelite and wet ground on rotating laps using a series of silicon carbide papers through 600 mesh. Final polishing was carried out first with fine diamond compound and then on a Syntron vibratory polisher in an aqueous media of Linde "B" polishing compound. The polished samples were etched with "R" etch--composed of 13.5 gm Benzalkonium Chloride, 35 ml Ethanol, 40 ml Glycerine, and 25 ml Hydrofluoric acid (20%)--by swabbing for 3-4 seconds.

For electron microscope examination collodion replicas were made from the surface of the etched specimens. The replicas were shadowed with palladium to increase contrast and reveal surface contours. Polystyrene latex spheres of approximately 3400 Å diameter were placed on the replicas prior to shadowing to indicate the angle and direction of shadowing and provide an internal standard for the measurement of magnification. The electron micrographs reproduced in this report are direct prints from the original negatives; consequently the polystyrene spheres appear black and the shadows appear white. Since the spheres are raised in the replica, a phase casting a shadow opposite to that cast by the latex spheres is in relief on the metal specimen; conversely, areas casting shadows in the same direction as cast by the latex spheres are depressions in the surface of the metal specimen and represent a phase that was attacked by the etchant.

RESULTS AND DISCUSSION

Data are reported which show that the original sheet stock exhibited the abnormal ratios of tensile to compressive yield strengths characteristic of the Bauschinger effect. The literature for the effect was reviewed from the viewpoint of the mechanism involved. Additional data are reported to show the introduction of the effect by prior creep. The directional properties of the sheet in relation to the Bauschinger effect were studied. A study was made of the relation of short time strain to creep strain by various paths in producing the effect. The report also includes the results of some structural studies made in relation to the general effects of prior creep on mechanical properties.

IDENTIFICATION OF THE BAUSCHINGER EFFECT IN C110M

The identification of the Bauschinger effect present in the as-received annealed C110M sheet (Heat A1172600) followed an inquiry into apparent discrepancies in the yield strengths. Preliminary data (Ref. 7) taken in the rolling direction indicated the compressive yield strength to be about 60-75 percent of the tensile yield strength in the temperature range tested--room temperature to 800°F. These results drew comments from personnel at the Republic Aviation Corporation citing experience that tensile and compressive strengths of C110M tend to be approximately equal. (Ref. 8) Steps were then taken at the University to resolve this anomaly. The steps, partially reported in Reference 1, included a study of the compression test procedures and a re-evaluation of the properties of the C110M stock. In addition, arrangements were made with Republic Aviation to exchange different lots of C110M sheet in order to provide independent checks of test procedures and also of the properties of the lot of C110M in question. A brief discussion of the results presented in Reference 1 follows.

The University's compression test fixture and procedures were confirmed to be in substantial accord with accepted techniques (Refs. 9 and 10). These included the use of an averaging extensometer, off-set grooved guide blocks, and the use of a torque wrench in setting a consistent support force. Data taken on other materials with this equipment was found to agree with accepted results. Further tests were then run on the C110M stock using a support force more than ten times greater than normal. This was found to have only a slight effect on yield strength and ruled out premature buckling as a factor in producing low compressive yield strengths.

Since the studies of the equipment and procedures failed to provide an answer to the yield strength discrepancy, attention was directed towards the test material itself. Examination of the data indicated that the lot of C110M in question had a high ratio of tensile yield strength to ultimate tensile strength while the absolute value of the compressive yield strength, although slightly low, was comparable to values reported by other laboratories (Ref. 9). This indicated that the high tensile yield strength was also a contributor to the low ratio of the compressive yield strength to the tensile yield strength. Additional tension and compression tests were then run on C110M sheet on hand from an earlier lot (Heat A5036) and on stock from Heat A50089 received from Republic Aviation in exchange for material from Heat A1172600. Comparative data from Republic Aviation was not received in time for inclusion in Reference 1.

The results of room temperature tests conducted at the University and Republic Aviation (Ref. 11) on Heats A1172600 and A50089 are summarized in Table 1 . Also included are some additional data from a Titanium Metallurgical Laboratory report (Ref. 9). Excellent agreement was obtained between the University and Republic Aviation on the tests of Heats A1172600 and A50089, thus confirming the original results obtained at the University and the reproducibility of the test procedures between the two laboratories. The only significant difference between the two laboratories was the consistently higher ductilities of the specimens tested at the University.

If all the heats except Heat A1172600 are considered "normal" the data indicated that "normal" C110M exhibits a ratio of tensile yield strength to ultimate tensile strength of 0.85-0.90, while the compressive yield strength/tensile yield strength ratio is about 1.0-1.05, ---- values consistent with Republic's initial comments. On the other hand, in material from Heat A1172600, the compressive yield strength/tensile yield strength ratio averaged only 0.78, while the tensile yield strength /ultimate tensile strength ratio averaged 0.97. These findings indicate that the as-received material from Heat A1172600 could be considered "abnormal". Reference to Table 1 indicates that while the abnormal material had a higher tensile strength and tensile yield strength than usual for the alloy, the main difference was a low compressive yield strength.

A plot of tension-compression stress-strain curves for "normal" and "abnormal" C110M, Figure 3, shows a marked difference in the shape of the curve between the tension and compression portions for the "abnormal" material. The tension portion exhibited a sharp "knee" at a stress slightly below the yield strength i.e. the proportional limit was high, while the compression curve deviated from elastic behavior at a low stress and was gradually rounded. The shapes of the curves resemble those for a variety of materials cited in the literature as exhibiting the Bauschinger effect (Refs. 12-16). The relative values of the tensile and compressive yield strengths of the C110M from Heat A1172600 are also consistent with the previously cited definition of the effect. (see P. 1)

On the basis of this evidence, it was concluded that the as-received C110M stock from Heat A1172600 (nominally hot rolled and annealed) was in a state of residual stress in tension in the rolling direction so as to exhibit a substantial Bauschinger effect when subsequently tested in tension and compression.

The source of the residual stress in this material is uncertain. Waisman and Yen (Ref. 17) and Maykuth (Ref. 18) indicated that cold stretching or cold forming resulting in residual stresses can produce Bauschinger effects in titanium and its alloys. Other sources of residual stress are processing operations or treatments involving differential heating and cooling rates, joining operations, machining, grinding, etc. It is likely that the effect in the present material resulted from some final straightening or leveling operation. As will be discussed later, appreciable Bauschinger effects involving decreased compressive yield strength are caused by plastic strains of up to 3 percent. Whatever the cause of the residual stress, its presence in the as-produced material was previously unsuspected and resulted in the apparently anomolous values of yield strength.

MECHANISM OF THE BAUSCHINGER EFFECT

In the 78 years since Bauschinger (Ref. 19) first observed the effect given his name, numerous investigators have sought an explanation for the phenomenon. The relative success of these undertakings was succinctly stated by Wooley (Ref. 16) who said (writing in 1953), " There is no adequate (quantitative) theory of the effect."

Qualitative explanations for the Bauschinger effect spring principally from the works of Heyn and of Masing (cited in the present report by reference to the reviews of Seitz(Ref. 20) and Barrett (Ref. 21). Essentially, these explanations depend on the action of residual microstresses produced due to differences in orientation between the non-isotropic grains of a polycrystalline material.

Consider, for example, a cylindrical, polycrystalline bar with a load applied in tension. If some grains are oriented so that they have a high yield strength to the applied tensile load, while others are oriented with their weaker direction presented to the load, then when the load is removed, the latter grains are brought in to a compressive strain by tensile stresses in the former. The final state of the unloaded material then consists of an equilibrium between tensile and compressive stresses in many small regions. Upon reloading, the stress in those grains in residual compression must be raised first to zero and then to the tensile yield strength before flow can begin. As Barrett stated, "the material has been work hardened for stresses in this direction." If, on the other hand, the material is subjected to a compressive stress after initial stressing in tension, the grains left in residual compression are already part way to their yield in compression and slight additional stresses will start plastic flow. Thus, the effective tensile yield strength of the aggregate is increased and the compressive yield strength is decreased. The converse would apply if the material is first subjected to compressive stress and then strained in tension.

The residual stresses between grains, appearing after release of the load, were called Heyn stresses. Masing used the principle to explain the phenomenon of creep recovery in a polycrystalline material by means of the relaxation of Heyn stresses.

Both Seitz and Barrett pointed out that such stresses could not be expected to appear in a homogeneously strained single crystal and therefore, according to this explanation, neither the Bauschinger effect nor creep recovery should be observed in a good single crystal. Seitz then refered to Sachs and Shoji's observation of the Bauschinger effect in single crystals of brass and explained it by a combination of the anisotropy of the metal and small inhomogeneties in plastic flow. Barrett mentioned a similar observation in single crystals of zinc and offered the view that the effects are due to stresses surrounding individual slip bands in single crystals or polycrystalline materials where relative displacement of the two sides of the slip band had occurred. Barrett also indicated that the Bauschinger effect may be produced after creep by the residual stresses left around slip bands, while if these stresses relax, an "aftereffect" is produced. Both Barrett (Ref. 21) and Corten and Elsesser (Ref. 14) referred to Zener's suggestion (Ref. 22) that the significant microscopic residual stress is a shearing stress in and around slip bands which generally traverse only part way through an individual crystal. This was apparently substantiated by observations in brass single crystals and cubically aligned polycrystalline copper.

Corten and Elsesser (Ref. 14) also indicated that foreign elements in a lattice could influence the presence of microscopic residual stress and "residual atomic forces", i.e. forces generated between particles on the atomic level as a result of misfits in regions of disorder, through the action of lattice flaws in the initiation of new slip bands. A method for removing the Bauschinger effect was suggested by Elsesser, Sidebottom, and Chang (Ref. 13). They showed that it could be eliminated in inelastically deformed low carbon steel or alpha brass, while an increased elastic limit was retained, by the application of slightly elevated temperature treatments as the material was maintained at a high stress level. Studies (Ref. 15) made on structural members overstrained until inelastic deformation occurred in the most strained fibers (for the purpose of inducing favorable macroscopic residual stresses) showed that after unloading, 60-percent less residual stress was obtained than the theoretical amount. This loss was attributed to the Bauschinger effect, i.e. inelastic deformation on unloading acted to cancel out the desired macroscopic stress. In brass and low carbon steel the full theoretical stress was induced if the material was heated (aged) at low temperatures (180° to 300°F) while the overstraining load was still applied. According to Corten and Elsesser (Ref. 14), aging under load removed the Bauschinger effect by reducing the "residual atomic forces" without materially affecting the macroscopic residual stresses. Experimental evidence indicated that the primary mechanism was a preferential rearrangement of copper and zinc atoms in brass and carbon and nitrogen atoms in steel by diffusion.

Wooley (Ref.16) studied Bauschinger effects in several face-centered and body-centered cubic metals and after comparing the results with the theories of a number of authors, concluded that there was no adequate quantitative theory. For instance, Masing's theory was unsatisfactory for deformations above 1 percent; a theory proposed by Brandenburger (Ref. 24) could not account for experimental results with pure metals; while an earlier explanation by Wooley, based on exhaustion theory was inadequate. Calculations made by Wooley showed that the maximum Bauschinger strain produced by textural stresses, i.e. those arising from orientation differences, could not account for the total effect observed. Wooley then concluded that the effect was largely a property of individual grains and a semi-quantitative explanation was presented in terms of the rearrangement of dislocations by a work-hardening mechanism.

REMOVAL OF THE BAUSCHINGER EFFECT FROM AS-PRODUCED HEAT A1172600

Examination of data from Reference 1 covering the effects of unstressed exposure on the mechanical properties of Heat A1172600 indicated that the Bauschinger effect could be materially reduced or eliminated from the as-produced material by suitable exposure to temperature. The following tabulation of yield strength ratios shows how 100 hours exposure at 800°F was instrumental in removing the Bauschinger effect while having only a small effect on the "normal" heats:

Effect of Unstressed Exposure for 100 hours at 800°F on Selected Strength Ratios of C110M Titanium at Room Temperature

Heat No.	Ratio: Tensile Y.S. / Ultimate T.S. As Prod.	Ratio: Tensile Y.S. / Ultimate T.S. 800°F-100 hrs.	Ratio: Compressive Y.S. / Tensile Y.S. As Prod.	Ratio: Compressive Y.S. / Tensile Y.S. 800°F-100 hrs.
A1172600 ("abnormal")	0.97	0.85	0.78	1.13
A50089 ("normal")	0.88	0.77	1.02	1.05
A5036 ("normal")	0.86	0.84	1.03	1.09

Note: Calculated from data in Reference 1, p. 19. Specimens taken in the sheet rolling direction.

Table 2 shows the effects of a number of different exposure temperatures and times on the room temperature strength ratios of Heat A1172600. These data indicate that exposure for 50 to 100 hours at 650°F was required to raise the room temperature compressive yield strength/tensile yield strength ratio to approximately 0.90. At 700°F a four hour exposure, the pre-heat time in creep-exposure tests, raised the ratio to 0.95 while an exposure for 10 hours increased the ratio to 0.99, and the longer times at 700°F and 800°F caused further increases.

Exposures for as long as 100 hours at 650° and 700°F did not reduce the tensile-yield strength/ultimate tensile strength ratio of Heat A1172600 below 0.92. The 800°F exposure, on the other hand, reduced this ratio to the range exhibited by "normal"material. The compressive yield strength/tensile yield strength ratio, however, then ranged from 1.12 to 1.14---slightly above "normal" behavior.

In tests conducted at elevated temperatures somewhat similar results were obtained. (Table 2) Ten hours exposure at 700°F was the threshold condition for a significant increase in the compressive yield strength/tensile yield strength ratio, while the tensile yield strength/ultimate yield strength ratio showed a tendency to decrease with increased temperature and time of exposure. (Limited data at elevated temperatures (Ref. 9) showed that the compressive yield strength/ tensile yield strength ratio of "normal" C110M was 1.07 at 400°F and 1.24 at 800°F).

The results obtained with the present material, Heat A1172600, which contained an unknown amount of residual stress applied in an unknown manner, compare favorably with the simple case where the stress is produced by cold stretching in tension. For this case, information on stress relief procedures has been summarized by Maykuth (Ref. 18).

Maykuth stated that for temperatures below 600°F, the exposure times needed to cause a significant reduction in residual stresses in C110M were impractically long. Although treatments of 15 minutes at 700°F were used, it was generally necessary to use higher temperatures for effective stress relief. For example, in material stretched 3 percent, a treatment of one hour at 825°F was effective in restoring the tensile and compressive yield strengths to their original values while after 2 percent pre-stretch, five minutes at 900°-1000°F reduced the tensile yield strength to the as-produced value.

Some evidence also exists to indicate that treatments at 700°F, or above can cause a slight increase in the tensile yield strength of pre-stretched material as the result of precipitation hardening from the formation of omega phase. (Ref. 18)

BAUSCHINGER EFFECTS INDUCED BY CREEP

In the earlier part of the present investigation (Ref. 1) it was shown that specimens of C110M subjected to creep in tension at either 650° or 700°F exhibited an increased tensile yield strength and decreased compressive yield strength in short-time tests conducted either at room temperature or the creep temperature. In some cases, the deformation included short-time plastic loading strain while in other cases it consisted solely of creep strain. In any event, it was found that residual stresses after plastic strain at sufficiently low elevated temperatures can be of sufficient magnitude to cause Bauschinger effects.

The very pronounced degree of the Bauschinger effects produced by creep exposure is shown by Figure 4 in which Maykuth's data for cold stretching C110M (Ref. 18) is compared with curves calculated from the data of Reference 1 for creep exposures of 10 hours at 650°, 700° or 800°F.

In Figure 4 the change in compression yield strength from the "recovered" value (exposure to temperature alone) is plotted against the total plastic strain obtained in the creep-exposure. This strain includes both short-time plastic loading strain and creep strain. Also included in Figure 4 is a table showing the effect of the 10 hours unstressed exposure on the compressive yield strength / tensile yield strength ratio. As indicated previously, the four hour pre-heat time at 700°F was sufficient to almost completely remove the original Bauschinger effect. On the other hand, the four hour pre-heat time at 650°F did not result in appreciable recovery prior to loading. Assuming the absolute yield strength after the 10 hour exposure at 700°F to be the "normal" value for this heat, the data of Maykuth were used to calculate the effect of cold stretching on the compressive yield strength of "normal" Heat A1172600. This relationship is plotted in Figure 5 together with the absolute strength values previously obtained. The zero strain intercepts in this plot refer of course to the conditions of unstressed exposure. From Figures 4 and 5 it is readily seen that the plastic strain from a 700°F creep exposure can cause a loss in short-time compressive yield strength almost as severe as that produced by cold-stretching.

In connection with this plot it should also be noted that the compressive yield strength after first decreasing rises as deformation is continued. This was observed both by Maykuth (Ref. 18) for C110M titanium and Waisman and Yen

(Ref. 17) for commercially pure titanium, stainless steel, and several aluminum alloys. This effect is attributed to strain hardening which eventually counteracts and overcomes the influence of the microresidual stresses causing the original loss of strength. Of the materials mentioned above, the maximum loss in strength, about 42 percent from the base value, occurred in C110M cold stretched 2-3 percent. The loss became less severe as the amount of cold-stretching was increased above 3 percent.

The extent of the creep-induced Bauschinger effect depends on the time and temperature at which the creep occurs and, possibly, the relative amounts of short-time strain and creep strain. Of course, in Heat A1172600, the picture is complicated by the original Bauschinger effect in the as-produced material. This is brought out by Figure 4 which shows that a greater relative decrease in compressive yield strength with increased plastic strain occurred for the condition which had a greater amount of recovery prior to loading---the 700°F exposure---while the material exposed at 650°F showed a much smaller decrease. However, as Figure 5 shows, the material crept at 650°F had an appreciably lower compressive yield strength to begin with.

The recovery in strength resulting from the unstressed exposure at 800°F was reduced only to a limited extent by the creep at this temperature. The explanation for this behavior is not immediately evident. Among the factors that could have counteracted the Bauschinger effect are the following:

1. Strengthening from transformation of beta. (Confirmed to some extent by metallographic evidence.)

2. Strain-aging.

3. Simultaneous recovery due to the higher creep temperature.

4. A possible transition in the mechanism of creep whereby the deformation processes governing the short-time room temperature strength may not be solely operative at the creep temperature. For example, the creep at 800°F could include a greater grain boundary contribution, thus lessening the tendency for the formation of residual stresses within the grains.

Furthermore, it appears that in addition to the creep temperature and total strain, the creep time had an effect on the subsequent yield strengths of the material. Figure 6 is a plot of room temperature compressive yield strength after creep at 700°F versus total strain for creep times of 10, 50 and 100 hours. (Again it should be noted that the four hour pre-heat period resulted in almost complete recovery prior to the application of the creep load.) The maximum loss in yield strength followed 10 hours creep at 700°F while the least effect followed 100 hours creep. A cross plot of these data for 1-percent total strain is presented in Figure 7. On this plot the value indicated for 1-percent cold stretching was estimated from Maykuth's data. Also indicated on this plot is the amount of short-time strain making up the total strain of 1-percent for the various creep times. This plot indicates that the longer the creep time, the less severe the loss of compressive strength, and incidentally, the smaller the fraction of short-time strain making up the total strain. To a lesser extent, the change in tensile yield strength was also governed by the creep time at 700°F. This is indicated in Figure 8, a plot of the relative changes at room temperature of both the tensile and compressive yield strength following 700°F creep. Figures 5 and 6 show that the shorter the exposure time to produce a given amount of creep at 700°F, the more pronounced is the subsequent Bauschinger effect. This time dependence suggests that recovery processes and/or metallurgical instabilities modify the deformation-dependent properties of the material.

EFFECT OF VARIABLE STRAIN PATHS ON MECHANICAL PROPERTIES AT ROOM TEMPERATURE.

The data discussed in the preceding sections on the effects of creep on mechanical properties were obtained from specimens which were maintained under constant load and temperature. If the load raised the stress above the proportional limit, rapid strain was introduced before creep occurred. The total plastic strain was composed of both rapid initial strain and creep strain mainly in the creep exposures at 650° and 700°F because high stresses were required to induce creep. At 800°F the stresses were below the proportional limit in most cases. It will be recalled that the creep specimens exposed at the lower temperatures exhibited substantially greater Bauschinger effects than those exposed at 800°F.

The question accordingly arose as to whether there was a difference in the effect of rapid strain and creep strain in so far as their effect on mechanical properties was concerned. Recovery during creep could be responsible for the reduced Bauschinger effect at the higher temperatures and longer exposure times. On the other hand, creep strain might not introduce a Bauschinger effect.

Accordingly experiments were undertaken in which strain was introduced by various paths. The conditions were selected to provide information on the relative roles of creep and rapid strain in the influence of recovery.

Exposure conditions of 100 hours at 700°F were selected. This permitted the introduction of 1 to 2 percent strain while keeping the loads below the proportional limit. Secondly, there was evidence that recovery occurred fairly rapidly at this temperature.

Several conditions of strain and recovery were investigated. Short time strain was introduced at the begining and at the end of 100 hours at 700°F. In addition, it was introduced at other time periods in order to vary the recovery conditions. Creep strains were also introduced under various conditions with and without accompanying short time strains.

The influence of the exposure conditions on properties were measured by tension and compression tests at room temperature. The results are tabulated in Tables 3 and 4, and shown graphically by Figures 9, 10, and 11. In both the Tables and Figures diagrams of each path are included in order to facilitate understanding of the manner in which the exposure was conducted.

In the path diagrams the abcissa is time and the ordinate is stress. The following code is used:

— - —	=	Exposure at no load.
|	=	Loading } Both loading and unloading are assumed to be instantaneous.
¦	=	Unloading }
+ + +	=	Specimen cooled under load (to minimize strain recovery)
↗	=	Creep

The graphical presentation of the results relates the property changes to two base conditions. The intercepts of the curves on the zero strain axis are the properties after 100 hours exposure without stress at 700°F. This point of origin was used because the main intent is to study the effect of strain at 700°F. The graphs also show the properties for the original sheet without any exposure to indicate the combined effects of heating and strain.

Proportional limit values for both tension and compression tests are included. Because the Bauschinger effect alters the complete stress-strain characteristics, it was felt that the proportional limit values in addition to 0.2-percent offset yield strengths would help clarify the effects.

Short-Time Strain Paths

The results of the tests, Table 3 and Figure 9, show the following:

1. Strain introduced rapidly at the end of the 100 hours of exposure to 700°F (Paths 2 and 4) increased tensile yield strengths and proportional limits in comparison to the values resulting from exposure without any strain. At the same time the compressive yield strengths and proportional limits were reduced. These changes are characteristic of the Bauschinger effect.

2. When the rapid strain was introduced beofre exposure (Path 1) or partially before exposure and partly at 50 hours (Path 3) the compressive yield strengths and proportional limits were unchanged in comparison to material exposed without strain.

3. Ultimate tensile strengths increased about the same whether the strain was introduced before or after exposure to 700°F. This suggests that some other factor was involved in addition to the residual stresses which cause the Bauschinger effect.

4. Ductility values were not appreciably changed by short time strain under any of the conditions investigated.

5. The changes in yield strengths and proportional limits were less when half of the strain was introduced after 50 hours of exposure and half at the end of the exposure period (Path 4) than when all the strain was introduced at the end of the exposure period (Path 2). Figure 10 shows that the changes were in proportion to the amount of plastic strain applied at the end of the exposure period. Apparently recovery from the influence of the strain introduced at 50 hours occurred during the subsequent 50 hours without stress.

6. It will be noted that about 0.5 percent strain at the end of the exposure period reduced the compressive yield strength and proportional limit values to about the same level as those of the unexposed material. There was little further change in these values as the result of increasing the strain to 2 percent.

7. Table 3 shows that a small amount of recovery of plastic deformation occurred by "creep" when specimens were held at 700°F after the introduction of rapid plastic strain. This is a normal result of heating after straining.

Creep Strain Paths

Creep was introduced by several different paths (Paths 5, 5a, 6, 7, 8, 9 and 10) and the effects on room temperature mechanical properties measured (Table 4 and Figure 11.) The results may be summarized as follows:

1. In all cases there was a substantial increase in ultimate strength, yield strength and proportional limit in tension. These were nearly proportional to the amount of strain. Ductility was also reduced in contrast to the short-time strain paths which did not change ductility.

2. Compressive yield strengths were practically unaffected by creep strain. Restricting the creep to the last 50 or 25 hours of exposure (Paths 6 and 9) resulted in some decrease. Holding at 700°F for the last 50 hours after the inducing creep for the first 50 hours (Path 7) resulted in some increase.

3. There was some decrease in compressive proportional limit for all cases except Path 7 where the specimens were held for the last 50 hours without stress.

4. In those cases where short time strain was introduced along with creep (Paths 5a, 10 and probably 8 and 9) the changes in tensile properties were not quite as marked as when creep alone was involved.

These results indicate that creep at 700°F did not result in as marked a Bauschinger effect as did short-time strain at the end of the exposure period. In fact the main indication of a Bauschinger effect was the somewhat reduced compressive proportional limit and the increase in tensile yield strengths, while the compressive yield strengths were unchanged.

The evidence for a time dependent strain-induced structural change increasing strengths in tension seems quite marked. Presumably if it were not for the weak Bauschinger effect from creep, the compressive strengths would also have been increased.

Summary of Effects of Rapid and Creep Strain

Plastic strain up to about 2 percent superimposed on the effects of holding C110M samples at 700°F for 100 hours had certain effects on mechanical properties at room temperature. Both rapid and creep strains increased ultimate and yield strengths and proportional limits in tension. Rapid strain did not cause as much increase in ultimate strength as did creep strain. Rapidly applied strains did not alter ductility in tension while creep strain reduced it somewhat. These changes occurred whether or not recovery periods without stress were included in the paths. The possible exception to this generality was an apparent reduction in the magnitude of the changes when rapid strain was combined with creep strain.

Compressive yield strengths were reduced by rapid strains applied at the end of 100 hours exposure to 700°F. Creep strains did not appreciably alter the compressive yield strengths except possibly for a slight reduction when the creep strain was introduced during the last 25 hours of exposure. Holding at 700°F without stress after creep resulted in increased compressive yield strength. Compressive proportional limits were reduced by rapid strain. Creep strains may have slightly reduced compressive proportional limits if there was no period of recovery without stress. About 0.5 percent plastic strain applied rapidly at the end of the exposure period reduced the compressive yield strength and proportional limit to about the same values as for the original sheet. Larger strains caused little further change.

The difference in the effects of creep strain or rapid strain on the ultimate strength and ductility indicates that there was a strain-activated structural change occurring during the creep-exposures. That is, creep strain was more effective than rapid strain. In addition, short time strain without the opportunity for recovery introduced a marked Bauschinger effect. On occasion this was superimposed on the effects of the strain-activated structural change. Furthermore, in the case of the compressive properties, the increased strength associated with the strain-activated structural change was offset by the Bauschinger effect introduced by creep. This resulted in little net change in the compressive properties rather than the increase to be expected from the structural change. Due to this factor there was an appreciable increase in the ratio of tensile yield strength to compressive yield strength after creep even though the compressive yield strength did not change. Only when there was opportunity for recovery after creep did the compressive properties increase in accordance with the structural change.

It is evident from the data that the intensity of the Bauschinger effect was reduced for creep in 100 hours in comparison to short time strain. As the data cited in primary section indicated, creep at 650° or 700°F introduces a marked Bauschinger effect. However, as the temperature and time period for creep is increased, the intensity of the effect is reduced and becomes negligible at sufficiently high temperatures and long times. For example, the effect of the time period was indicated in Figure 7. If creep can occur, there is certainly opportunity for stress relief. Thus when creep occurs under conditions where there is relatively little or no strain hardening resulting from the creep, simultaneous recovery should eliminate the Bauschinger effect. The data indicate that creep strains up to 2.5 percent in 100 hours at 700°F represent a condition where there is partial recovery from the creep-induced Bauschinger effect.

Short-time strains involved in the Bauschinger effect noted for creep specimens exposed at lower test temperatures undoubtedly contributed to the Bauschinger effects. However, the data reported in this section indicate that the creep was also a contributing factor.

DIRECTIONAL PROPERTIES OF C110M SHEET

In the previous studies of C110M the properties were determined on specimens taken from the sheet stock in the direction of rolling. It was established on the basis of the observed Bauschinger effect in the as-produced material that the residual stress causing the effect, although of an unknown amount and unknown direction of application, was in tension in the rolling direction. It should however be recognized that residual stresses have components at all angles to the direction of the plastic deformation producing the stress (Ref. 17). Furthermore, axial elongation of metals is accompanied by lateral contraction or an axial tensile stress has a lateral component in compression. Figure 12, taken from the data of Waisman and Yen (Ref. 17) shows that commercially pure titanium stretched and then tested laterally (90°) to the stretching direction exhibits increased compressive yield strength and decreased tensile yield strength, a behavior opposite to that of the same material when tested in the stretching direction. The magnitude of the effect appears to be about the same for both testing directions.

In addition to the superimposed directionality of residual stresses, a more common source of the directionality of mechanical properties in sheet materials arises from preferred orientations developed during rolling and possibly from phases occurring as stringers in the rolling direction.

In recognition of these factors a study was carried out of the effect of orientation on mechanical properties of the C110M stock investigated. Specimen blanks from Heat A1172600 were cut from sheet stock at orientations of 30°, 45°, 60°, and 90° to rolling in the configuration illustrated in Figure 13. Testing was carried out at room temperature on material in the original condition and following stressed exposures at 700°F for 10 hours, a condition producing a large Bauschinger effect in longitudinal specimens.

Tests at room temperature on as-produced sheet gave the results in Table 5 and Figure 14 for the effect of specimen orientation. There was no difference in the tensile or compressive yield strength at 30° to the rolling direction. The tensile yield strength was higher than the compressive yield strength between 0° and 30° to the rolling direction. From 30° to 90° the compressive strength was higher. The maximum difference in both cases was of the order of 25,000 to 30,000 psi. The compressive yield strength ranged from 110,000 to 162,000 psi while the tensile yield strength varied only about 10,000 psi.

In addition to the yield strengths, the other mechanical properties of the sheet exhibited a dependence on the orientation. A minimum in ultimate strength and a maximum in ductility occurred at approximately 45° to rolling, while minimum ductility was observed at 60° to rolling. As would be expected the tensile yield strength was much closer to the ultimate strength between 0° and 45° than between 45° and 90°. Apparent maxima also occurred in the tensile and compressive modulus values, although these values should not be regarded as precise inasmuch as they were calculated from slopes of the stress-strain curves.

The variations in properties with orientation are a consequence of both the Bauschinger effect and of preferred orientations developed during working of the material. This topic of preferred orientation has been thoroughly discussed by Barrett (Ref. 21) and Richards (Ref. 24) among others.

The mechanical properties following 10 hours exposure without stress at 700°F, Table 5, are plotted in Figure 15. Comparison with Figure 14 shows that the stress relief afforded by this exposure resulted in an increase in the tensile or compresssive yield strength at those orientations where the original residual stress had caused a reduction in strength. Thus, the compressive yield strength was increased at the orientation of 0° to 45° to rolling and the tensile yield strength was increased in the 60-90° orientations. In addition, the tensile yield strength increased in relation to the ultimate tensile strength in the 45-90° orientations. The ultimate strength, ductility and relative modulii were little affected.

The effects of the exposure on the ratio of tensile yield strength to ultimate tensile strength and compressive yield strength to tensile yield strength were calculated and are tabulated in Table 6 and plotted as a function of orientation in Figure 16. The ratio of compressive yield strength to tensile yield strength, a measure of the Bauschinger effect, varied, depending on orientation, from 0.76 to 1.25 before exposure and 1.01 to 1.09 after exposure. The slightly higher yield strength ratio at the orientations of 45°-90° to rolling is probably related to the preferred orientation of the sheet.

The effects on mechanical properties of creep exposure for 10 hours at 700°F (Table 5) are presented graphically in Figure 17. In this figure the data are plotted both as functions of the creep deformation and the total plastic deformation. The data show that regardless of the specimen orientation, deformation of the material in tension had the following general effects on room temperature mechanical properties: The ultimate and tensile yield strengths increased; the tensile yield strength increased relative to the ultimate tensile strength; the compressive yield strength decreased; and the ductility decreased. The decrease in compressive yield strength at 0° was in relation to material heated for 10 hours without stress. Hardness changes, however, were small and inconsistent. (Table 5)

Both the deformation behavior and the magnitude of the changes in mechanical properties depended to some extent on the specimen orientation. Examination of the data in Table 5 indicates that extensive plastic deformation occurred during loading of several specimens taken from the sheet at 30° or 45° to the sheet rolling direction. In two cases, the deformation was so rapid and so great that it could only be estimated from the full scale travel of the extensometer system. This behavior is graphically shown in Figure 18, a plot of stress versus loading deformation. For comparison an average stress-strain curve for short-time tensile tests of longitudinal (0° to rolling) specimens at 700°F is included in Figure 18. This figure shows that the specimens taken at intermediate orientations (30°, 45°, 60°) had appreciably greater loading deformations at a given stress than did the 0° and 90° specimens. Examination of the individual loading curves for these tests indicated that a lower proportional limit could account for this behavior.

The creep behavior of these specimens is indicated in Figure 19, a plot of stress versus creep strain reached in 10 hours at 700°F. This plot shows that at a given stress the transverse (90°) specimens crept somewhat less than longitudinal (0°) specimens, while the specimens oriented at 30°, 45°, and 60° crept a greater amount. Therefore, for a given amount of total plastic strain, the 0° and 90° specimens contained a higher proportion of creep strain than did the 30°, 45°, and 60° specimens.

In Figure 16, the ratio of compressive yield strength to tensile yield strength is plotted as a function of specimen orientation both for total plastic strains of 0.5 and 1.0 percent and for 1.0 percent creep strain (Data tabulated in Table 6). The relative shape of the yield-strength-ratio curves with orientation is the same for all the deformation parameters, the curves being merely displaced towards lower values as the amount of deformation increased. As Figure 16 indicates, the yield strength ratio (a measure of the Bauschinger effect) is sensitive to the sheet orientation, being lowest for longitudinal (0°) specimens and highest for transverse (90°) specimens. A total plastic strain of 0.5 percent in 10 hours at 700°F resulted in ratios at 0° as low as in the as-produced material. The yield strength ratio for transverse (90°) specimens after 0.5 percent total plastic strain in 10 hours was the same as that following the four hour pre-heat for the longitudinal condition. However, it should be recognized that an original Bauschinger effect was initially present in the transverse direction in the as-produced material and the relative decrease in yield ratio was similar for both specimen orientations. The absolute values of the tensile and compressive yield strengths as a function of total plastic strain are plotted for all orientations in Figure 20. For plastic strains of less than 2 percent, the longitudinal (0°) specimens had the lowest compressive yield strength while the transverse (90°) direction had the highest tensile yield strength.

Another view of these results can be gained from an examination of Figure 21. This plot shows the percent change in mechanical properties with respect to the value for the unstressed exposure as a function of deformation. Thus, the effect of deformation can be evaluated independent of the variation in the initial properties resulting from preferred orientations in the sheet. The orientation apparently did not affect the relative increase in ultimate tensile strength with increased creep strain. The relative loss of ductility showed a variable, but possibly not significant dependence on the orientation. For instance, the apparently unchanged ductility of the 60° specimen is not considered significant since a specimen tested to a large total strain was not available for this condition. The same reasoning is probably valid in explaining the curve for the transverse (90°) orientation.

Specimen orientation does appear to be of some significance in the response of the room temperature yield strengths to prior plastic strain at 700°F. The longitudinal specimens (0°) had the greatest relative loss in compressive yield strength, while the effect in the transverse (90°) specimens was the least severe of any orientation for total strains up to 1.5 percent. No data were available to indicate that the curve for the 90° specimens would level off at greater strains as did the others. At a strain of 2 percent the increase in tensile yield strength ranged from about 5 to 12 percent, while the decrease in compressive yield ranged from approximately 15 to 29 percent. It appears, therefore, that the response of the C110M sheet material to prior creep in tension is manifested in an increased ultimate tensile strength and decreased ductility that tends to be fairly independent of the specimen orientation, while the changes in the yield strengths are somewhat orientation sensitive.

A further factor is the gross microstructure of the material. Figure 22 is a photomicrograph of the longitudinal surface of the C110M alloy showing how the alpha grains were strung out in the rolling direction. Indicated on the photograph are the relative orientations of the various specimens. This shows that in the 90° direction of testing the vast majority of the alpha-beta interfaces are normal to the direction of creep and tensile testing while the opposite is the case for specimens taken in longitudinal (0°) direction. The gross difference in the grain boundary orientation with respect to the applied stress might account for some of the differences in behavior between these two orientations and the behavior of the intermediate orientations.

STRUCTURAL STUDIES OF C110M AND CORRELATION WITH MECHANICAL PROPERTIES

During the present investigation metallographic studies of C110M were extended to include the use of the electron microscope. Previous studies, limited to optical examination at magnifications up to 1000x, were inconclusive, revealing no apparent structural changes that could be correlated with the mechanical properties following creep-exposure (Ref. 1). The more detailed study made possible by the electron microscope led to the discovery of a phase transformation in the hot rolled and annealed structure, probably the beta-to-omega-to-alpha transformation, apparently stress-activated at 700°F and time and temperature controlled at 800°F. Even then, an entirely clear cut correlation of structural changes with mechanical properties was not apparent.

An optical micrograph at 500x and an electron micrograph at 3500x of the as-produced condition are presented in Figure 23. Representative electron micrographs at 8200x magnification are presented in Figures 24 through 33. In conjunction with Figure 22, the lower magnification pictures show that the as-produced condition consisted of somewhat variable-sized, elongated alpha grains in a beta matrix.

Following creep-exposure for 100 hours at 650°F (Figure 25) or unstressed exposure for 10 hours at 700°F (Figure 26), no structural changes were apparent. However, a 10 hour creep exposure to a large deformation at 700°F (Figure 27) caused a slight roughening of the matrix indicating the initiation of the beta-to-omega transformation. A specimen subjected to 100 hours unstressed exposure at 700°F also showed evidence of roughening (Figure 28), while a specimen crept for 100 hours at 700°F exhibited large amounts of a well-defined, rodlike precipitate-probably alpha (Figure 29). Lesser amounts of this precipitate were also observed in a specimen crept for 50 hours at 700°F. (The alpha phase resulting from this reaction will be termed secondary alpha to distinguish it from the much larger particles of original alpha.)

Exposure without stress at 800°F for 10 hours (Figure 30) or 100 hours (Figure 32) resulted in the appearance of larger secondary alpha particles. Creep-exposures at 800°F (Figures 31 and 33) did not appear to change significantly the relative amount and distribution of the secondary alpha although its size was perhaps increased over that produced by the unstressed exposures. However, the time of exposure at 800°F appeared to have a greater influence on the amount of secondary alpha produced than did the presence of stress. On the other hand, the precipitation at 700°F appeared to have been stress-activated.

Although the photomicrographs reveal striking changes in the structure as a result of exposure, the change in the mechanical properties was, in most cases, relatively small. The room temperature mechanical properties of these specimens are summarized in Table 7. Interpretation of the data was rendered difficult by the necessity of accounting for the relative contributions of the creep-induced Bauschinger effect and the phase transformation. Hardness changes were limited to a range of 3-6 points Rockwell "C" and were generally consistent with the strengths.

As discussed in the section on the influence of strain paths, the structural change probably accounts for the property changes which appeared to be stress-activated and time dependent. This discussion also pointed out that a Bauschinger effect induced by creep masked changes in compressive properties due to the structural changes. Also it contributed to the increases in the properties in tension.

CONCLUSIONS

Creep-exposure of C110M sheet at 650° or 700°F caused appreciable changes in the short-time tensile and compressive yield strengths characteristic of the Bauschinger effect. After creep in tension, the tensile yield strength was increased and the compressive yield strength was decreased. The Bauschinger effect after creep at 800°F was slight. A structural instability was found to occur during creep exposure at 700° and 800°F, accounting for slightly increased strength and decreased ductility, although the possibility of strain hardening also exists. The magnitude of the Bauschinger effect induced by creep-exposure at 700°F approached the values given in the literature for cold-stretching.

The investigation was complicated by the presence of a Bauschinger effect in the as-produced material. This was removed during the pre-heat period prior to creep testing at 700° or 800°F but not at 650°F. Consequently, the additional effect of 650°F creep-exposure was not as great as would have been found if the tests had been conducted on stress-free material.

Studies of variable strain-paths at 700°F indicated that there was no apparent difference between short-time plastic strain and long-time creep strain in inducing the Bauschinger effect. However, simultaneous recovery during creep caused the effect to be lessened for a given deformation as the creep time was increased. Unstressed exposure, generally at 700°F or above, was effective in removing the Bauschinger effect.

A study of the effect of specimen orientation showed that the magnitude of the creep-induced Bauschinger effect depended to some extent on the orientation of the applied stress with respect to the sheet rolling direction. The deformation properties also exhibited a dependence on the orientation.

The structural instability during testing was a stress-activated breakdown of non-equilibrium beta to form a secondary alpha phase. This was revealed by electron microscope studies.

REFERENCES

1. Gluck, J. V., Voorhees, H. R., and Freeman, J. W., "Effect of Prior Creep on Mechanical Properties of Aircraft Structural Metals, Part III. C110M Titanium Alloy" WADC Technical Report 57-150 Part III, January, 1958

2. Gluck, J. V., Voorhees, H. R., and Freeman, J. W., "Effect of Prior Creep on Mechanical Properties of Aircraft Structural Metals (2024-T86 Aluminum and 17-7PH Stainless)" WADC Technical Report 57-150, January, 1957

3. Gluck, J. V., Voorhees, H. R., and Freeman, J. W., "Effect of Prior Creep on Mechanical Properties of Aircraft Structural Metals, Part II, 17-7PH (TH 1050 Condition)." WADC Technical Report 57-150 Part II, November 1957

4. Gluck, J. V. and Freeman, J. W., "Effect of Prior Creep on Short-Time Mechanical Properties of 17-7PH Stainless Steel (RH 950 Condition Compared to TH 1050 Condition)" WADC Technical Report 59-339, March, 1959

5. Gluck, J. V. and Freeman, J. W., "Effect of Prior Creep on the Mechanical Properties of a High-Strength, Heat-Treatable Titanium Alloy, Ti-16V-2.5Al" WADC Technical Report 59-454, March, 1959

6. Lyman, T. (editor) Metals Handbook, p. 2, American Society for Metals, Cleveland, Ohio (1948)

7. Gluck, J. V., Voorhees, H. R., and Freeman, J. W., "Sixth Progress Report to Materials Laboratory, Wright Air Development Center on Effect of Prior Creep on Mechanical Properties of Aircraft Structural Metals" (Contract AF 33(616)-3368) May 25, 1957

8. Letter from J. C. O'Brien, Republic Aviation Corp., Farmingdale, New York, Dated August 1, 1957 (Ref: 57-4582)

9. Hyler, W. S., "An Evaluation of Compression-Testing Techniques for Determining Elevated Temperature Properties of Titanium Sheet" Titanium Metallurgical Laboratory, Battelle Memorial Institute, TML Report No. 43 (June 8, 1956)

10. "Uniform Testing Procedures for Sheet Materials" Department of Defense Titanium Sheet Rolling Program. Defense Metals Information Center, Battelle Memorial Institute. DMIC Report No. 46D, September 12, 1958

11. Letter from R. F. Wichser, Republic Aviation Corp., Farmingdale, New York, dated May 6, 1958

12. Templin, R. L. and Sturm, R. G., "Some Stress-Strain Studies of Metals" Journal of the Aeronautical Sciences, p. 189. (March 1940)

13. Elsesser, T. M., Sidebottom, O. M., and Corten, H. T., "The Influence of Aging on the Bauschinger Effect in Inelastically Strained Beams" Trans. ASME, vol, 74, No. 8, pp. 1291-1296 (November 1952)

14. Corten, H. T. and Elsesser, T. M., "The Effect of Slightly Elevated Temperature Treatment in Microscopic and Submicroscopic Residual Stresses Induced by Small Inelastic Strains in Metals" Trans. ASME, vol. 74, No. 8, pp. 1297-1302 (November 1952)

15. Sidebottom, O. M. and Chang, C-T., "Influence of the Bauschinger Effect in Inelastic Bending of Beams" Proceedings First U. S. Nat'l. Congress of Applied Mechanics, ASME, New York, 1952, pp. 631-639

16. Wooley, R. L., "The Bauschinger Effect In Some Face-Centered and Body-Centered Cubic Metals" Phil. Mag. Ser. 7, vol. 44, No. 353, pp. 597-618 (June 1953)

17. Waisman, J. L. and Yen, C. S., "Effect of Forming in Mechanical Properties", Proc, ASTM Pacific Coast Meeting, September 17-21, 1956, pp. 33-44

18. Maykuth, D. J., "Stress Relief, Annealing, and Reactions with Atmosphere of Titanium and Titanium Alloys", Paper Delivered at ASM Titanium Conference, Los Angeles, California, March 25-29, 1957; also issued as a Memorandum dated May 24, 1957 by Titanium Metallurgical Laboratory, (now Defense Metals Information Center), Battelle Memorial Institute, Columbus Ohio

19. Bauschinger, J., Ziviling, vol. 27, p. 289 (1881)

20. Seitz, F., Physics of Metals, pp. 145-149, McGraw-Hill Book Company, New York, 1943

21. Barrett, C. S., Structure of Metals, pp. 359-60, 367, McGraw-Hill Book Company, New York, (Second Edition) 1952

22. Zener, C. in Symposium on the Cold Working of Metals, p. 180, American Society for Metals, Cleveland, 1949-----Elasticity and Anelasticity of Metals, pp. 145-146, University of Chicago Press, Chicago, 1948

23. Richards, T. Ll., "Preferred Orientation of Non-Ferrous Metals", article in Progress in Metal Physics, vol. 1, Chalmers, B. (ed.), p. 281, Interscience Publishers, New York, 1949

24. Brandenburger, H., Schweiz. Arch. Angew. Wiss. Tech., vol. 13, p. 232, 268 (not consulted)

TABLE 1

COMPARISON OF TENSION AND COMPRESSION PROPERTIES AT ROOM TEMPERATURE FOR SEVERAL HEATS OF C110M TITANIUM

				Tension Properties					Compression Properties			
Heat No.	Data Source	Number of Tests	Range/ Average	Ultimate Strength (1000 psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Modulus, E x 10^6	Ratio: Ten. Yield / Ten. Ult.	Number of Tests	0.2% Offset Yield Strength (1000 psi)	Modulus, E (x 10^6 psi)	Ratio: Comp. Yield / Ten. Yield
A-1172600*	U of M	9	Range	144-152	139-147	20.5-24.0	15.8-16.9	--	9	105-111	15.8-16.7	--
			Average	146.2	142.3	22.4	16.5	0.98		108.1	16.2	0.76
A-1172600*	R.A.C.	12	Range	144-149	135.5-145.5	13.5-17	15.0-15.7	--	7	103.8-120.2	16.4-16.9	--
			Average	146.7	140.3	15.5	15.3	0.96		112.8	16.7	0.80
A-50089**	U of M	3	Range	127.8-130.5	114-115.2	24-26.8	14.7-14.9	--	3	115-117.3	15.3	--
			Average	129.4	114.5	25.5	14.8	0.88		115.8	15.3	1.01
A-50089**	R.A.C.	12	Range	131-133.8	113.6-119.1	16-19	14.3-15.0	--	3	120.3-123.5	16.6-16.9	--
			Average	132.0	117.2	17.0	14.7	0.89		121.9	16.7	1.04
A-5036***	U of M	2	Range	130-136	113-116	--	14.4-15.1	--	2	116.5-119.5	15.7-16.1	--
			Average	133	114.5	--	14.8	0.86		118.0	15.9	1.03
A-32233-11	Boeing	3	Range	--	120.5-121.8	--	16.0-16.4	--	3	129.1-130.7	16.4-16.5	--
			Average	133	121.1	--	16.3	--		130.0	16.5	1.07
A-40006-Me	Boeing	3	Range	--	134.4-137.5	--	15.5-16.0	--	3	131.9-135.8	16.1-16.6	--
			Average		136.0	--	15.7	--		134.0	16.4	0.99
A-40006-M1	Boeing	3	Range	--	136.2-137.9	--	16.1-16.6	--	3	140.6-144	16.4-16.8	--
			Average	--	137.1	--	16.4	--		142.0	16.7	1.03
Unknown	Armour	3	Range	--	120.5-124.0	--	15.6-16.0	--	3	125.1-128.1	16.3-16.6	--
			Average	--	121.9	--	15.8	--		126.7	16.4	1.03

Data Sources:

U. of M. -- University of Michigan
R.A.C. -- Republic Aviation Corporation
Boeing -- Boeing Airplane Corporation (Data from TML Report No. 43)
Armour -- Armour Research Foundation (Data from TML Report No. 43)

* Material tested for WADC TR 57-150 Pt III
** Material furnished by Republic Aviation for checking purposes.
*** Material remaining from an earlier research project--reported in WADC TR 54-54 "A Study of Creep of Titanium and Two of Its Alloys" by J. V. Gluck and J. W. Freeman.

TABLE 2

EFFECT OF UNSTRESSED EXPOSURES ON SELECTED STRENGTH RATIOS OF C110M (HEAT A1172600)

Exposure Temp(°F)	Conditions Time (hrs)	Test Temp. (°F)	Ratio: Tensile Yield / Ultimate Tensile *	Ratio: Compressive Yield / Tensile Yield *
PART I				
As-Produced		Room	0.97	0.78
650	10	Room	0.94	0.79
	50	Room	0.95	0.88
	100	Room	0.94	0.92
700	4**	Room	0.93	0.95
	10	Room	0.97	0.99
	50	Room	0.92	1.00
	100	Room	0.95	0.96
800	10	Room	0.91	1.12
	50	Room	0.89	1.14
	100	Room	0.85	1.13
PART II				
As-Produced		650	0.87	0.64
650	10	650	0.84	0.64
	50	650	0.85	0.63
	100	650	0.87	0.68
As-Produced		700	0.88	0.61
700	10	700	0.85	0.85
	50	700	0.83	0.80
	100	700	0.77	0.92
As-Produced		800	0.91	0.66
800	10	800	0.79	0.88
	50	800	0.74	1.03
	100	800	0.81	0.75

* Note: Calculated from data in Ref. 1, Tables 2, 5, 6, 9, and 10.

** Note: This exposure corresponds to the holding time prior to load application in the stressed exposure tests.

TABLE 3

EFFECT OF EXPOSURE TO SHORT-TIME STRAIN PATHS ON ROOM TEMPERATURE MECHANICAL PROPERTIES OF C110M

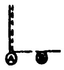
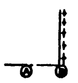
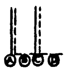
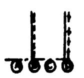
Path	Nominal Plastic Def. -%	Specimen No.	Exposure Sequence	Deformation: Total Loading (Elastic + Plastic)	Deformation: Plastic Loading	Deformation: Plastic Creep	Deformation: Total Plastic	Type of Test	Ultimate Tensile Strength	0.2% Offset Yield	Proportional Limit	Elongation (%)	R.A. (%)	Modulus
None	None	Average	As-produced	--	--	--	--	Tensile	146,211	142,889	93,600	22.4	31.3	16.5
None	None	Average	As-produced	--	--	--	--	Comp.	--	108,111	55,800	--	--	16.2
No stress	None	1A3A	700°F-100 hr	--	--	--	--	Tensile	146,500	140,000	111,000	19.5	32.0	15.4
		3A4	700°F-100 hr	--	--	--	--	Tensile	154,000	146,000	127,000	24.0	32.2	15.9
									150,250	143,000	119,000	21.7	32.1	15.6
		2CD32	700°F-100 hr	--	--	--	--	Comp.	--	134,000	111,000	--	--	15.7
		3AB13	700°F-100 hr	--	--	--	--	Comp.	--	132,000	112,000	--	--	15.0
		2AB33	700°F-100 hr	--	--	--	--	Comp.	--	136,500	102,000	--	--	15.3
										134,200	108,000			15.3
1) Pre-Strain	0.5	3A25	A. At 700°F-91,000 psi-Load-	0.94	0.30	--	0.30							
			B. Unload-Hold 100 hr	--	--	-0.04	0.26	Tensile	157,000	147,500	125,000	20.7	27.2	15.4
	1.5	2C29	A. At 700°F-96,000 psi-Load-	1.54	0.81	--	0.81							
			B. Unload-Hold 100 hr	--	--	-0.05	0.77	Tensile	154,000	146,000	125,000	23.3	28.4	15.0
	1.5	2CD29	A. At 700°F-97,000 psi-Load-	2.35	1.65	--	1.65							
			B. Unload-Hold 100 hr	--	--	-0.01	1.64	Tensile	162,000	151,500	134,000	25.5	28.2	14.7
	0.5	1C16	A. At 700°F-91,000 psi-Load-	1.64	0.96	--	0.96							
			B. Unload-Hold 100 hr	--	--	0.03	0.99	Comp.	--	130,000	104,000	--	--	15.3
	1.5	2A23	A. At 700°F-96,000 psi-Load-	1.90	1.21	--	1.21							
			B. Unload-Hold 100 hr	--	--	-0.06	1.15	Comp.	--	137,000	99,000	--	--	15.9
2) Post-Strain	0.5	3C23	A. At 700°F-Hold 100 hrs											
			B. 91,000 psi load-Cool under load	1.14	0.41	--	0.41	Tensile	172,000	168,000	125,000	12.3	22.8	15.1
	1.0	2CD12	A. At 700°F-Hold 100 hrs											
			B. 97,000 psi load-Cool under load	1.70	0.98	--	0.98	Tensile	164,000	164,000	160,000	20.0	30.0	15.6
	1.5	2CD18	A. At 700°F-Hold 100 hrs											
			B. 96,000 psi load-Cool under load	1.37	0.66	--	0.66	Tensile	156,000	156,000	124,000	18.3	28.0	14.7
	1.5	1AB22	A. At 700°F-Hold 100 hrs											
			B. 97,000 psi load-Cool under load	2.45	1.80	--	1.80	Tensile	159,000	159,000	133,000	22.5	32.8	14.7
	0.5	2A33	A. At 700°F-Hold 100 hrs											
			B. 91,000 psi load-Cool under load	1.18	0.61	--	0.61	Comp.	--	102,000	54,000	--	--	[illegible]
	1.5	1AB8	A. At 700°F-Hold 100 hrs											
			B. 96,000 psi load-Cool under load	2.65	1.92	--	1.92	Comp.	--	104,0[illegible]	56,000	--	--	15.6
3) Cyclic Prestrain	0.5	2AB23	A. At 700°F-89,500 psi load	0.96	0.28	--	0.28							
			B. Unload-Hold 50 hrs	--	--	-0.02	0.26							
			C. 89,500 psi load	0.81	0.12	--	0.38							
			D. Unload-Hold 50 hrs			-0.02	0.36	Tensile	152,500	144,500	122-130,000	22.0	36.0	15.5
	1.5	3A16	A. At 700°F-93,000 psi load	1.17	0.40	--	0.40							
			B. Unload-Hold 50 hrs	--	--	-0.02	0.38							
			C. 93,000 psi load	0.88	0.16	--	0.54							
			D. Unload-Hold 50 hrs			-0.05	0.49	Tensile	157,500	149,500	123-131,000	20.5	31.0	14.9
	1.5	1CD2	A. At 700°F-94,000 psi load	2.17	1.53	--	1.53							
			B. Unload-Hold 50 hrs	--	--	-0.04	1.49							
			C. 94,000 psi - load	1.12	0.22	--	1.71							
			D. Unload-hold 50 hrs	--	--	-0.03	1.68	Tensile	159,000	152,000	131,000	22.5	28.0	15.7
	0.5	1A12	A. At 700°F-92,000 psi load	0.84	0.13	--	0.13							
			B. Unload-Hold 50 hrs	--	--	-0.02	0.11							
			C. 92,000 psi load	0.83	0.15	--	0.26							
			D. Unload-Hold 50 hrs	--	--	--	0.26	Comp.	--	129,500	99,000	--	--	15.3
	1.5	3AB19	A. At 700°F-94,000 psi load	1.97	1.27	--	1.27							
			B. Unload-Hold 50 hrs	--	--	--	--							
			C. 96,000 psi load	--	--	--	--							
			D. Unload-Hold 50 hrs	0.96	0.25	--	1.52	Comp.	--	136,500	104,000	--	--	16.8
4) Cyclic Post-Strain	0.5	1CD27	A. At 700°F-Hold 50 hrs	--	--	--	--							
			B. 89,500 psi load	1.05	0.50	--	0.50							
			C. Unload-Hold 50 hrs	--	-0.05	--	0.45							
			D. 89,500 psi load:	1.00	0.30	--	0.75							
			E. Unloaded and cooled	--	--	--	--	Tensile	156,500	152,000	143,000	20.0	30.0	14.9
	1.5	3C31	A. At 700°F-Hold 50 hrs	--	--	--	--							
			B. 93,500 psi load	1.19	0.54	--	0.54							
			C. Unload-Hold 50 hrs	--	--	--	--							
			D. 93,500 psi load	0.86	0.23	--	0.77							
			E. Stop-Cool under load	--	--	--	--	Tensile	155,500	154,000	144,000	24.5	29.6	16.0
	0.5	2C18	A. At 700°F-Hold 50 hrs	--	--	--	--							
			B. 92,000 psi load	1.19	0.54	--	0.54							
			C. Unload-hold 50 hrs	--	--	-0.02	0.52							
			D. 92,000 psi load	0.84	0.22	--	0.74							
			E. Unloaded and cooled	--	--	--	0.74	Comp.	--	109,700	78,000	--	--	16.8
	1.5	1CD22	A. At 700°F-Hold 50 hrs	--	--	--	--							
			B. 94,000 psi load	1.62	0.67	--	0.67							
			C. Unload-Hold 50 hrs	--	--	--	0.67							
			D. 96,000 psi load	1.10	0.40	--	1.07	Comp.	--	117,500	83,500	--	--	16.5
			E. Stop-cool under load	--	--	--	--							

TABLE 4

EFFECT OF EXPOSURE TO CREEP PATHS ON ROOM TEMPERATURE MECHANICAL PROPERTIES OF C110M

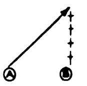
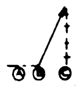
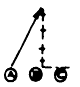
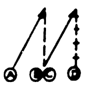
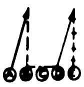
Path	Nominal Plastic Deformation	Specimen No.	Exposure Sequence	Deformation: Total Loading	Deformation: Plastic Loading	Deformation: Plastic Creep	Deformation: Plastic Total Plastic	Type of Test	Room Temperature Properties After Exposure: Ultimate Tensile Strength (psi)	0.2% Offset Yield (psi)	Proportional Limit (psi)	Elongation (%)	R.A. (%)	Modulus, E x 10^6 psi
5) Creep Only	0.5	1C27	A. At 700°F-51,000 psi load	0.37	nil	--	--							
			B. Creep 100 hrs-Cool under load	--	--	0.58	0.58	Tensile	159,000	150,000	134,000	18.0	29.0	14.8
	1.5	3AB6	A. At 700°F-68,000 psi load	0.56	nil	--	--							
			B. Creep 100 hrs-Cool under load	--	--	1.41	1.41	Tensile	168,000	159,000	140,000	18.8	25.0	14.5
	0.5	2A11	A. At 700°F-51,000 psi load	0.34	nil	--	--							
			B. Creep 100hrs-Cool under load	--	--	0.39	0.39	Comp.	---	137,500	86,000	--	--	15.6
	1.5	1CD16	A. At 700°F-68,000 psi load	0.48	nil	--	--							
			B. Creep 100hrs-Cool under load	--	--	2.35	2.35	Comp.	---	128,000	87,000	--	--	15.8
	1.5	3CD25	A. At 700°F-68,000 psi load	0.57	0.06	--	0.06							
			B. Creep 100hrs-Cool under load	--	--	2.71	2.77	Comp.	---	132,000	90,000	--	--	15.6
6) Post Creep	0.5	3AB16	A. At 700°F-Hold 50hrs											
			B. 62,000 psi load	0.49	nil	--	--							
			C. Creep 50hrs-Cool under load	--	--	0.47	0.47	Tensile	156,000	151,000	97,000	20.5	27.7	15.2
	1.5	1AB12	A. At 700°F-Hold 50hrs											
			B. 75,000 psi load	0.70	0.04	--	0.04							
			C. Creep 50hrs-Cool under load	--	--	1.04	1.08	Tensile	163,300	158,000	116-141,000	20.0	34.2	15.5
	0.5	1C29	A. At 700°F-Hold 50hrs											
			B. 71,000 psi load	0.57	nil	--	--							
			C. Creep 50hrs-Cool under load	--	--	0.59	0.59	Comp.	---	124,000	77,000	--	--	15.9
	1.5	2CD6	A. At 700°F-Hold 50hrs											
			B. 75,000 psi load	0.59	0.09	--	0.09							
			C. Creep 50hrs-Cool under load	--	--	0.75	0.84	Comp.	---	126,500	79,500	--	--	15.7
7) Pre-Creep	0.5	2A22	A. At 700°F-62,000 psi load	0.47	nil	--	--							
			B. Creep 50hrs-remove load	--	--	0.36	0.36							
			C. Hold 50hrs-no stress	--	--	-0.02	0.34	Tensile	157,000	146,000	131,000	21.0	37.0	15.2
	1.5	3A6	A. At 700°F-71,000 psi load	0.59	0.02	--	0.02							
			B. Creep 50hrs-remove load	--	--	0.87	0.89							
			C. Hold 50hrs-no stress	--	--	-0.02	0.87	Tensile	168,500	153,000	126,000	17.3	25.6	15.5
	0.5	1A25	A. At 700°F-63,000 psi load	0.56	nil	--	--							
			B. Creep 50 hrs-remove load	--	--	0.56	0.56							
			C. Hold 50hrs-no stress	--	--	--	0.56	Comp.	---	142,500	108,000	--	--	16.7
	1.5	3AB22	A. At 700°F-72,000 psi load	0.58	0.05	--	0.05							
			B. Creep 50hrs-remove load	--	--	0.72	0.77							
			C. Hold 50 hrs-no stress	--	--	--	0.77	Comp.	---	136,500	100,000	--	--	16.4
	1.5	2CD8	A. At 700°F-71,000 psi load	0.57	0.04	--	0.04							
			B. Creep 50hrs-remove load	--	--	1.07	1.11							
			C. Hold 50hrs-no stress	--	--	-0.08	1.03	Comp.	---	141,000	109,000	--	--	16.3
8) Cyclic Creep	0.5	2AB22	A. At 700°F-45,000 psi load	0.35	nil	--	--							
			B. Creep 50hrs-remove load	--	--	0.17	0.17							
			C. 45,000 psi load	0.34	nil	--	0.17							
			D. Creep 50 hrs-Cool under load	--	--	0.22	0.39	Tensile	158,500	146,000	125,000	16.8	29.8	15.5
	1.5	3CD31	A. At 700°F-68,000 psi load	0.55	nil	--	--							
			B. Creep 50hrs-remove load	--	--	0.71	0.71							
			C. 68,000 psi load	0.50	nil	--	0.71							
			D. Creep 50hrs-Cool under load	--	--	1.69	2.40	Tensile	165,000	156,000	130,000	15.5	19.4	14.5
	0.5	3CD26	A. At 700°F-45,000 psi load	0.30	nil	--	--							
			B. Creep 50 hrs-remove load	--	--	0.21	0.21							
			C. 45,000 psi load	0.28	nil	--	0.21							
			D. Creep 50hrs-Cool under load	--	--	0.19	0.40	Comp.	---	137,600	96,000	--	--	16.6
	1.5	1CD34	A. At 700°F-68,000 psi load	0.56	0.06	--	0.06							
			B. Creep 50hrs-remove load	--	--	0.58	0.64							
			C. 68,000 psi load	0.48	nil	--	0.64							
			D. Creep 50 hrs-Cool under load	--	--	1.32	1.96	Comp.	---	132,500	90,000	--	--	16.3
	1.5	2C6	A. At 700°F-68,000 psi load	0.59	nil	--	--							
			B. Creep 50hrs-remove load	--	--	0.56	0.56							
			C. 68,000 psi load	0.50	nil	--	0.56							
			D. Creep 50hrs-Cool under load	--	--	1.12	1.68	Comp.	---	135,000	80,000	--	--	16.5
9) Interrupted Creep	0.5	1AB25	A. At 700°F-58,000 psi load	0.45	nil	--	--							
			B. Creep 25 hrs-remove load	--	--	0.17	0.17							
			C. Hold 50hrs-(beam only)	--	--	--	0.17							
			D. 58,000 psi load	0.46	nil	--	0.17							
			E. Creep 25hrs-Cool under load	--	--	0.23	0.40	Tensile	156,000	151,000	143,000	20.5	32.0	15.2
	1.5	3CD23	A. At 700°F-73,000 psi load	0.56	0.08	--	0.08							
			B. Creep 25hrs-remove load	--	--	0.40	0.48							
			C. Hold 50 hrs	--	--	-0.01	0.47							
			D. 73,000 psi load	0.60	0.06	--	0.53							
			E. Creep 25hrs-Cool under load	--	--	0.76	1.29	Tensile	167,000	161,000	150,000	19.5	27.5	15.3
	0.5	1A8	A. At 700°F-58,000 psi load	0.48	nil	--	--							
			B. Creep 25hrs-remove load	--	--	0.21	0.21							
			C. Hold 50 hrs	--	--	-0.02	0.19							
			D. 58,000 psi load	0.49	nil	--	0.19							
			E. Creep 25hrs-Cool under load	--	--	0.35	0.54	Comp.	---	139,000	100,000	--	--	17.1
	0.5	1C2	A. At 700°F-69,000 psi load	0.58	0.05	--	0.05							
			B. Creep 25hrs-remove load	--	--	0.27	0.32							
			C. Hold 50 hrs	--	--	-0.07	0.25							
			D. 69,000 psi load	0.59	0.07	--	0.32							
			E. Creep 25 hrs-Cool under load	--	--	0.43	0.75	Comp.	---	126,000	82,000	--	--	15.4
	1.5	2CD11	A. At 700°F-73,000 psi load	0.56	0.08	--	0.08							
			B. Creep 25hrs-remove load	--	--	0.44	0.52							
			C. Hold 50hrs	--	--	--	0.52							
			D. 73,000 psi load	0.62	0.12	--	0.64							
			E. Creep 25hrs-Cool under load	--	--	0.73	1.37	Comp.	---	129,800	86,000	--	--	16.2

TABLE 4 (CONTINUED)
EFFECT OF EXPOSURE TO CREEP PATHS ON ROOM TEMPERATURE MECHANICAL PROPERTIES OF C110M

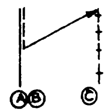
Path	Nominal Plastic Deformation	Specimen No.	Exposure Sequence	Deformation: Total Loading	Deformation: Plastic Loading	Deformation: Plastic Creep	Deformation: Plastic Total Plastic	Type of Test	Room Temperature Properties After Exposure: Ultimate Tensile Strength (psi)	0.2% Offset Yield (psi)	Proportional Limit (psi)	Elongation (%)	R.A. (%)	Modulus, E x 10^6psi
10) Pre Strain plus Creep	0.5	3AB4	A. At 700°F-89,500 psi load	0.98	0.26	--	0.26							
			B. Reduce load to 34,000 psi	0.55	--	--	0.26							
			C. Creep 100 hrs-Cool under load	--	--	0.26	0.52	Tensile	163,000	153,000	139,000	21.5	28.3	15.1
	1.0	1C22	A. At 700°F-80,000 psi load	0.75	0.16	--	0.16							
			B. Reduce load to 57,000 psi	--	--	--	0.16							
			C. Creep 100 hrs-Cool under load	--	--	0.85	1.01	Tensile	167,000	156,000	149,000	19.5	28.0	17.0
	1.5	1CD29	A. At 700°F-92,000 psi load	1.19	0.49	--	0.49							
			B. Reduce load to 56,000 psi	0.93	--	--	0.49							
			C. Creep 100 hrs-Cool under load	--	--	1.04	1.53	Tensile	165,500	155,600	146,000	18.3	27.6	14.8
	0.5	2AB11	A. At 700°F-89,500 psi load	0.95	0.19	--	0.19							
			B. Reduce load to 34,000 psi	0.45	--	--	0.19							
			C. Creep 100 hrs-Cool under load	--	--	0.23	0.42	Comp.	---	132,500	88,000	--	--	15.8
	1.5	3AB25	A. At 700°F-92,000 psi load	0.90	0.28	--	0.28							
			B. Reduce load to 56,000 psi	0.71	--	--	0.28							
			C. Creep 100 hrs-Cool under load	--	--	0.78	1.06	Comp.	---	135,000	88,000	--	--	15.7
	1.5	2C8	A. At 700°F-80,000 psi load	0.76	0.14	--	0.14							
			B. Reduce load to 65,000 psi	--	--	--	0.14							
			C. Creep 100 hrs-Cool under load	--	--	1.47	1.61	Comp.	---	134,000	83,000	--	--	16.4
Data from WADC TR 57-150 Pt III	0.5	3A33A	A. At 700°F-36,000 psi load	0.25	nil	--	--							
			B. Creep 100 hrs-Cool under load	--	--	0.26	0.26	Tensile	148,000	141,000	120,000	20.5	28.8	16.5
	1.0	2A7A	A. At 700°F-51,000 psi load	0.36	nil	--	--							
			B. Creep 100 hrs-Cool under load	--	--	0.32	0.32	Tensile	149,000	143,000	115,000	21.7	32.9	15.2
	2.0	1A26A	A. At 700°F-63,000 psi load	0.50	0.04	--	0.04							
			B. Creep 100 hrs-Cool under load	--	--	1.78	1.82	Tensile	162,000	149,000	115,000	17.3	26.2	16.1
	3.0	3AB11	A. At 700°F-69,000 psi load	0.51	0.05	--	0.05							
			B. Creep 100 hrs-Cool under load	--	--	1.89	1.94	Tensile	162,000	152,000	125,000	15.0	23.8	15.2
	0.5	2CD26	A. At 700°F-36,000 psi load	0.27	nil	--	--							
			B. Creep 100 hrs-Cool under load	--	--	0.31	0.31	Comp.	---	136,000	89,000	--	--	16.4
	1.0	3AB29	A. At 700°F-51,000 psi load	0.38	nil	--	--							
			B. Creep 100 hrs-Cool under load	--	--	0.67	0.67	Comp.	---	131,000	90,000	--	--	16.2
	2.0	3C14	A. At 700°F-63,000 psi load	0.51	0.05	--	0.05							
			B. Creep 100 hrs-Cool under load	--	--	0.84	0.89	Comp.	---	121,000	83,000	--	--	16.2
	3.0	1C30	A. At 700°F-70,000 psi load	0.61	0.07	--	0.07							
			B. Creep 100 hrs-Cool under load	--	--	2.91	2.98	Comp.	---	114,000	79,000	--	--	16.1

TABLE 5

EFFECT OF SPECIMEN ORIENTATION ON ROOM TEMPERATURE MECHANICAL PROPERTIES OF C110M AFTER 10 HOURS PRIOR CREEP-EXPOSURE AT 700°F

	Exposure Conditions							Room Temperature Short-Time Mechanical Properties After Exposure						
Spec. No.	Temp. (°F)	Time (hrs)	Stress (psi)	Total Load. Def. (%)	Plastic Load. Def. (%)	Creep Def. (%)	Total Plastic Strain (%)	Type of Test	Ult. Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%/2 inches)	Reduction of Area (%)	Modulus, E (10^6 psi)	Hardness R"C"
								Specimens Taken in Rolling Direction *						
(avg. of 9)	not exposed		--	--	--	--	--	Tensile	146,200	142,900	22.4	31.3	16.5	33.4
(avg. of 9)	not exposed		--	--	--	--	--	Comp.	--	108,000	--	--	16.2	--
1CD15	700	10	none	--	--	--	--	Tensile	143,000	140,000	23.8	34.0	15.4	39.1
3CD33	700	10	none	--	--	--	--	Tensile	146,000	--	24.0	27.9	15.4	38.7
1A4	700	10	56,000	0.43	nil	0.12	0.12	Tensile	138,000	135,000	21.0	30.0	14.7	38.5
3AB8	700	10	79,000	0.62	0.10	0.17	0.27	Tensile	149,000	144,000	23.2	31.4	15.5	36.6
2AB16	700	10	93,000	1.77	1.07	0.96	2.03	Tensile	150,500	149,500	21.0	31.2	15.2	37.9
3CD14	700	10	100,000	3.76	3.00	5.44	8.44	Tensile	177,000	175,000	7.8	18.2	15.6	34.2
1CD24	700	10	none	--	--	--	--	Comp.	--	147,000	--	--	16.1	--
3CD9	700	10	none	--	--	--	--	Comp.	--	136,000	--	--	15.7	--
1CD33	700	10	56,000	0.43	nil	0.11	0.11	Comp.	--	125,000	--	--	16.4	--
2A2	700	10	82,000	0.62	nil	0.32	0.32	Comp.	--	115,000	--	--	15.3	--
3C27	700	10	90,500	1.27	0.58	0.66	1.24	Comp.	--	94,400	--	--	16.8	--
1AB18	700	10	92,000	2.16	1.45	1.43	2.88	Comp.	--	103,000	--	--	16.6	--
								Specimens Taken 30° to Rolling Direction*						
S4A-T32	not exposed		--	--	--	--	--	Tensile	142,400	140,800	29.0	43.7	13.8	34
S4A-T37	not exposed		--	--	--	--	--	Tensile	140,000	138,000	26.0	36.2	13.7	36
									141,200	139,400	27.5	40.0	13.8	35
S4C-C11	not exposed		--	--	--	--	--	Comp.	--	140,500	--	--	19.0	--
S4C-C14	not exposed		--	--	--	--	--	Comp.	--	143,200	--	--	18.7	--
										141,850	--	--	18.9	--
S4A-T30	700	10	none	--	--	--	--	Tensile	139,000	139,000	27.5	45.5	14.5	--
S4A-T36	700	10	80,000	0.98	0.33	0.47	0.80	Tensile	146,000	146,000	25.5	40.6	14.5	--
S4A-T35	700	10	88,000	3.97(est)	3.0 (est)	1.71	4.70(est)	Tensile	162,500	162,500	11.0	35.5	14.7	--
S4C-C12	700	10	none	--	--	--	--	Comp.	--	140,000	--	--	16.8	--
S4C-C13	700	10	none	--	--	--	--	Comp.	--	141,000	--	--	16.8	--
S4A-T31	700	10	80,000	0.96	0.25	0.47	0.72	Comp.	--	112,000	--	--	15.4	--
S4A-T33	700	10	88,000	1.90	1.22	3.34	4.56	Comp.	--	115,000	--	--	17.6	--
								Specimens Taken 45° to Rolling Direction *						
S4C-T1	not exposed		--	--	--	--	--	Tensile	136,200	134,400	20.5	49.7	15.1	30
S4C-T7	not exposed		--	--	--	--	--	Tensile	131,000	--	27.0	46.2	14.7	35
S4C-T5	not exposed		--	--	--	--	--	Tensile	136,200	129,900	19.0	46.3	15.1	36
									134,500	132,200	22.1	45.7	14.9	33.3
S4C-C1	not exposed		--	--	--	--	--	Comp.	--	147,700	--	--	18.2	--
S4C-C3	not exposed		--	--	--	--	--	Comp.	--	149,500	--	--	18.3	--
										148,600	--	--	18.2	--
S4C-T10	700	10	none	--	--	--	--	Tensile	136,000	135,000	26.5	49.0	14.6	36
S4C-T6	700	10	75,000	0.99	0.40	0.34	0.74	Tensile	150,000	150,000	22.0	44.5	14.9	--
S4C-T3	700	10	90,500	3.15	2.5 (est)	2.00	4.5 (est)	Tensile	160,700	159,000	8.5	37.0	15.6	37
S4C-C6	700	10	none	--	--	--	--	Comp.	--	150,500	--	--	17.0	--
S4C-C4	700	10	none	--	--	--	--	Comp.	--	148,000	--	--	19.9	--
S4C-T2	700	10	78,000	1.00	0.39	0.37	0.76	Comp.	--	121,500	--	--	15.2	--
S4C-T9	700	10	88,000	4.5 (est)	3.8 (est)	4.10	7.9	Comp.	--	118,000	--	--	15.0	--
								Specimens Taken 60° to Rolling Direction *						
S4A-T67	not exposed		--	--	--	--	--	Tensile	146,000	120,500	21.0	39.4	13.6	35
S4A-T60	not exposed		--	--	--	--	--	Tensile	145,000	139,000	11.0	14.1	13.9	36
									145,500	129,750	16.0	26.7	13.8	35.5
S4C-C8	not exposed		--	--	--	--	--	Comp.	--	160,500	--	--	19.3	--
S4C-C10	not exposed		--	--	--	--	--	Comp.	--	164,000	--	--	22.3	--
										162,250	--	--	20.8	--
S4A-T65	700	10	none	--	--	--	--	Tensile	144,000	144,000	15.0	16.3	15.2	--
S4A-T61	700	10	80,000	0.90	0.40	0.41	0.81	Tensile	153,000	153,000	18.5	40.8	15.2	--
S4A-T66	700	10	88,000	1.15	0.48	0.76	1.24	Tensile	153,000	153,000	15.5	43.3	16.3	--
S4C-C7	700	10	none	--	--	--	--	Comp.	--	151,000	--	--	16.4	--
S4C-C9	700	10	none	--	--	--	--	Comp.	--	162,000	--	--	17.7	--
S4A-T64	700	10	80,000	0.89	0.24	0.39	0.63	Comp.	--	119,000	--	--	16.6	--
S4A-T62	700	10	90,000	1.48	0.78	1.37	2.15	Comp.	--	115,500	--	--	16.3	--
								Specimens Taken 90° to Rolling Direction *						
T44	not exposed		--	--	--	--	--	Tensile	149,000	134,000	21.0	29.8	15.8	37.9
T43	not exposed		--	--	--	--	--	Tensile	145,500	131,000	21.8	33.0	16.0	37.0
									147,250	132,500	21.4	31.4	15.9	37.4
T41	not exposed		--	--	--	--	--	Comp.	--	162,000	--	--	16.3	--
T42	not exposed		--	--	--	--	--	Comp.	--	153,000	--	--	16.9	--
										157,500	--	--	16.6	--
T4-AT5	700	10	none	--	--	--	--	Tensile	156,200	152,000	27.5	33.6	15.9	36
T4A-T6	700	10	90,500	0.81	0.20	0.38	0.58	Tensile	162,500	162,500	19.0	33.3	16.6	35
T4A-T8	700	10	96,000	1.37	0.80	0.90	1.70	Tensile	166,300	166,300	19.0	19.7	16.6	--
T47	700	10	none	--	--	--	--	Comp.	--	161,500	--	--	16.1	--
T4A-T10	700	10	92,000	0.96	0.35	0.49	0.84	Comp.	--	144,500	--	--	17.0	--
T4A-T7	700	10	97,000	1.05	0.45	0.72	1.17	Comp.	--	146,000	--	--	16.0	--
T4A-T9	700	10	100,000	1.02	0.40	1.22	1.62	Comp.	--	137,000	--	--	16.6	--

* Diagram of sheet sampling procedure given in Figure 13

TABLE 6

EFFECT OF ORIENTATION AND EXPOSURE CONDITIONS ON SELECTED STRENGTH RATIOS OF C110M TITANIUM

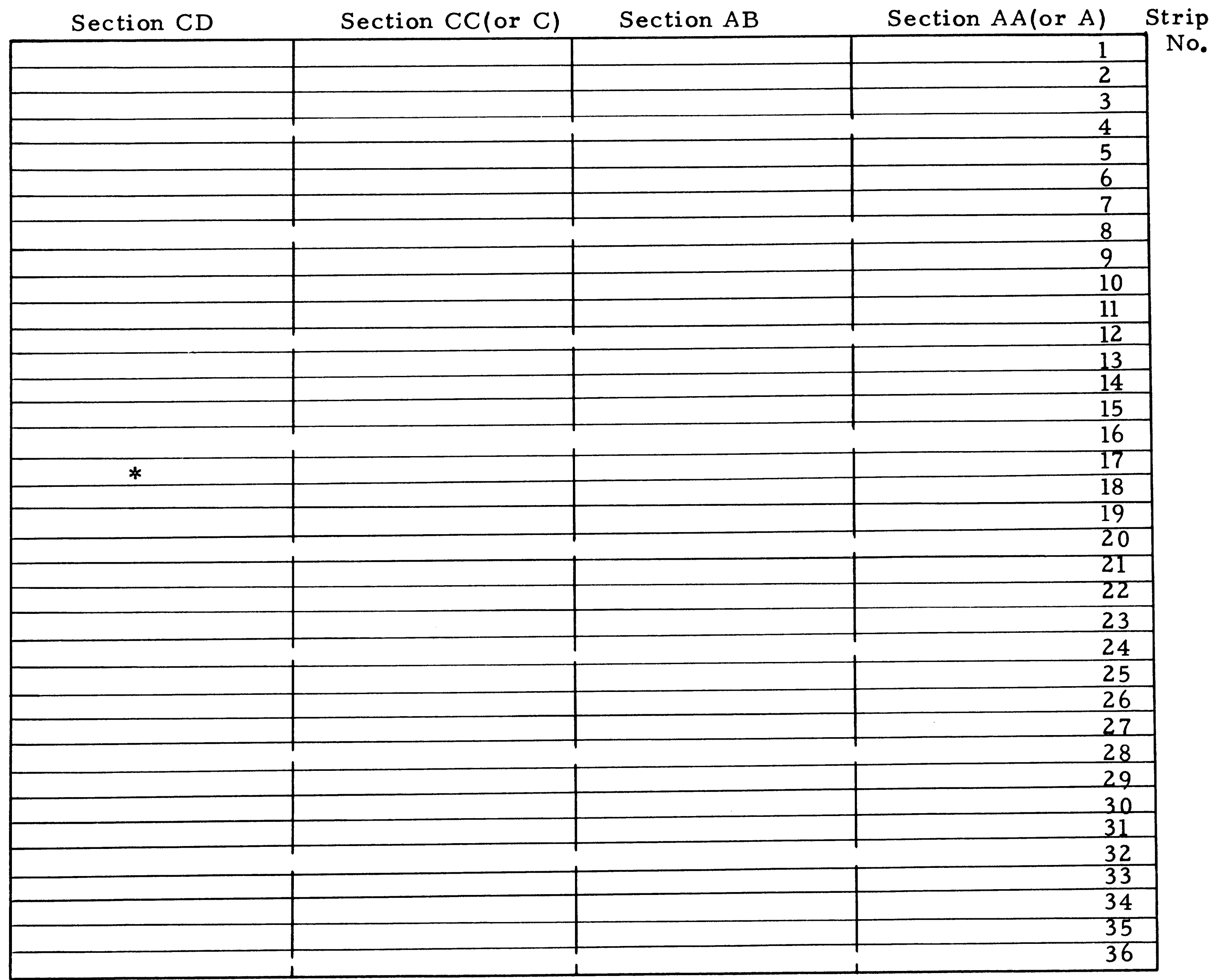
	Ratio: Tensile Yield / Ultimate Tensile		Ratio: Compressive Yield / Tensile Yield			
Orientation*	As Produced	Unstressed Exposure 10 hr-700°F	As Produced	Unstressed Exposure 10 hr-700°F	10 hr-700°F 1% Total Plastic Strain	10 hr-700°F 0.5% Total Plasti Strain
0°	0.98	0.97	0.76	1.01	0.69	0.77
30°	0.99	1.00	1.02	1.01	0.77	0.83
45°	0.98	0.99	1.12	1.11	0.81	0.90
60°	0.88	1.00	1.25	1.09	0.77	0.85
90°	0.90	0.97	1.18	1.06	0.88	0.96

* Orientation with respect to sheet rolling direction.

TABLE 7

MECHANICAL PROPERTIES OF METALLOGRAPHIC SPECIMENS

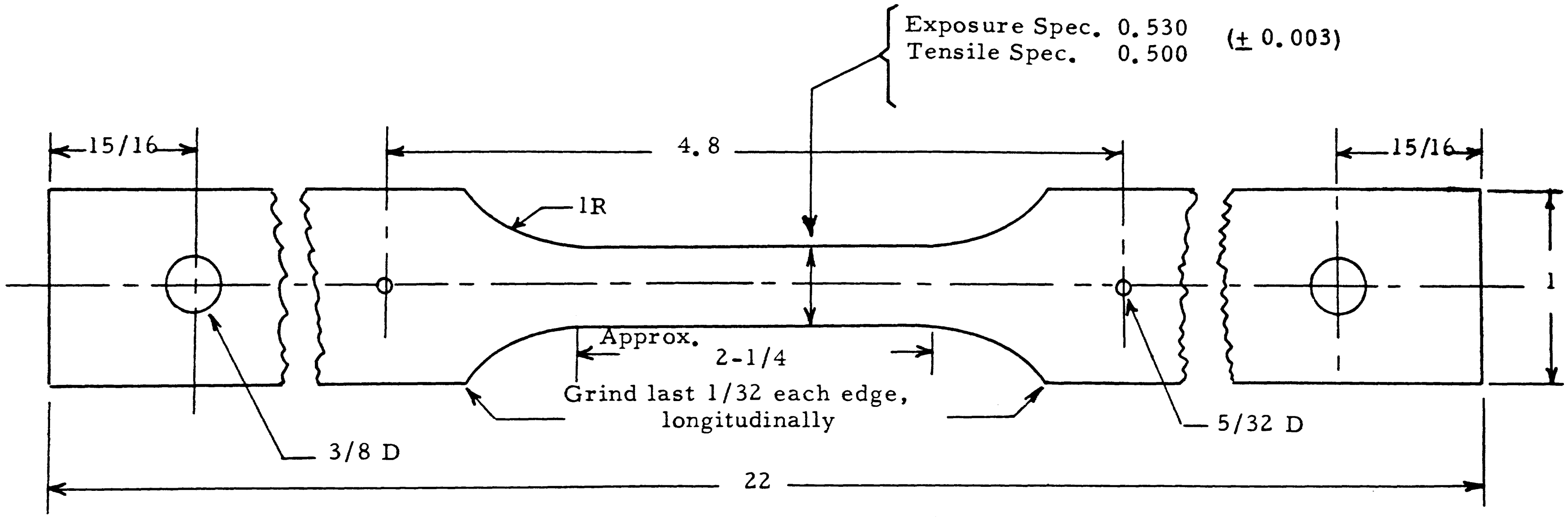
Figure No.	Specimen No.	Exposure	Room Temperature Mechanical Properties After Exposure: Ultimate Tensile(psi)	Tensile Yield (psi)	Est. Creep Yield(psi)	Elongation (%)	Hardness Rockwell"C"
21		As-produced	146,200	142,900	108,100	22.4	33.4
22	3A8	650°-100hr-0.4% def.	151,000	147,000	120,000	21.0	37.5
23	1CD15	700°-10hr-no stress	143,000	140,000	141,500	23.8	35.0
24	3CD14	700°-10hr-8.4% def.	177,000	175,000	90,000	7.8	34.2
25	3A4	700°-100hr-no stress	154,000	146,000	133,000	24.0	38.5
26	1A26A	700°-100hr-1.81% def.	162,000	149,000	118,000	17.3	39.4
27	1A15A	800°-10hr-no stress	146,000	133,000	150,000	24.0	35.1
28	1CD11	800°-10hr-0.33% def.	144,000	134,000	133,000	22.5	36.0
29	2CD31	800°-100hr-no stress	147,000	125,000	138,500	19.3	34.1
30	1C3C	800°-100hr-2.67% def.	145,000	130,000	129,000	19.5	33.1



Sheet Dimensions: 36x90x0.064 inches
Strip Dimensions: 22 (approx)x1x0.064 inches
Sheets Numbered 1, 2, 3, or 4 (arbitrarily)

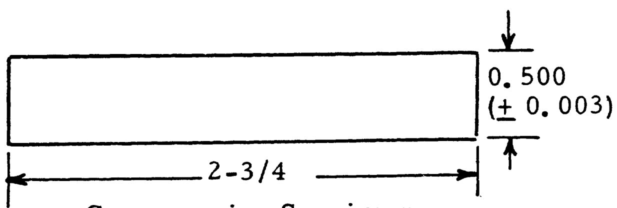
Specimen Code: (Sheet)(Section)(Strip)
*Example: Strip labeled * is 2CD17T, i.e. a tensile specimen from Strip 17 Section CD of Sheet 2.

Figure 1. - Sampling Procedure for Sheets of C110M Titanium Alloy



Tensile or Creep-Exposure Specimen

DO NOT SCALE
ALL DIMENSIONS IN INCHES



Compression Specimen

ALL SPECIMENS
FULL SHEET THICKNESS
0.064 INCHES

Figure 2. - Details of Test Specimens

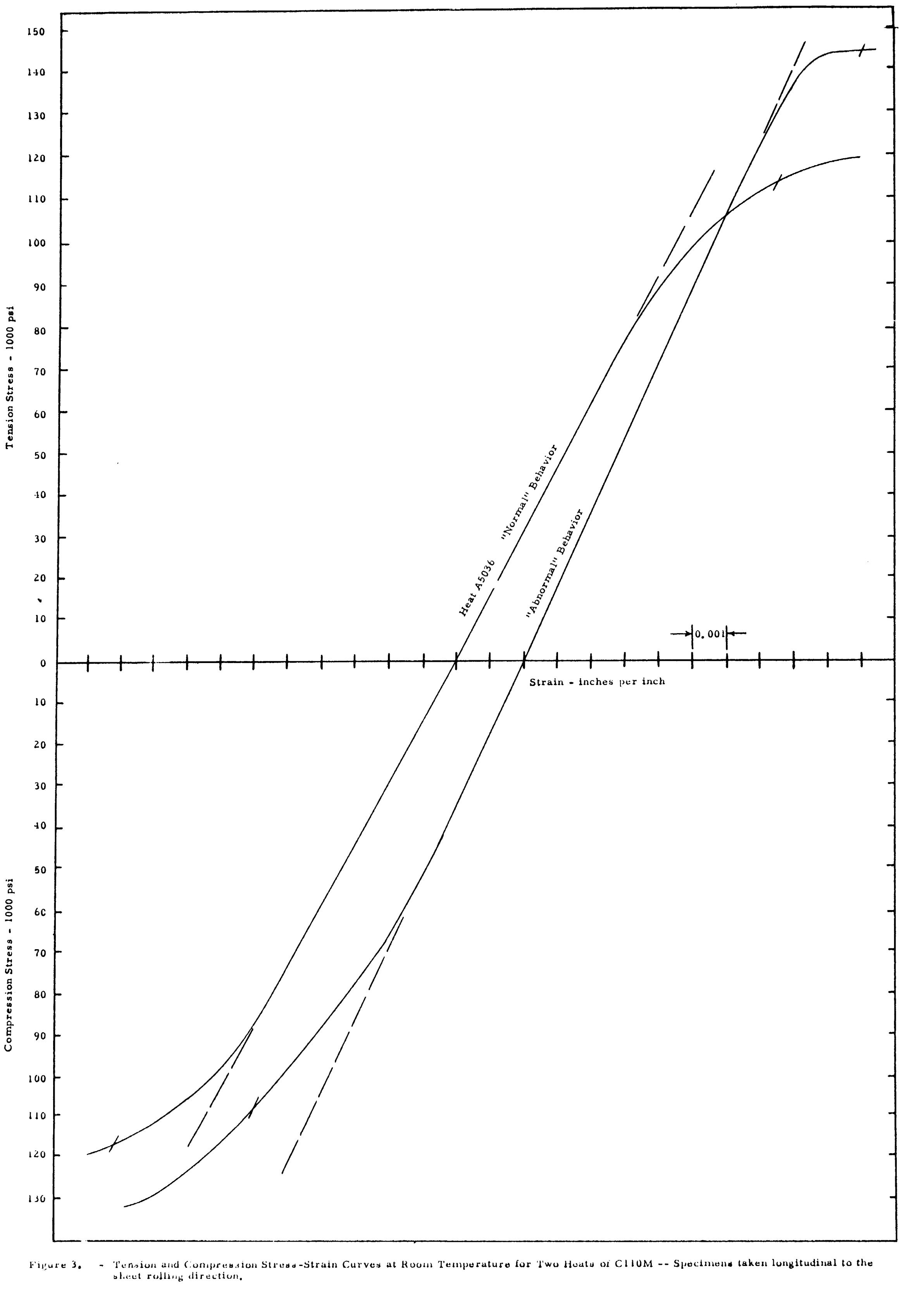


Figure 3. - Tension and Compression Stress-Strain Curves at Room Temperature for Two Heats of C110M -- Specimens taken longitudinal to the sheet rolling direction.

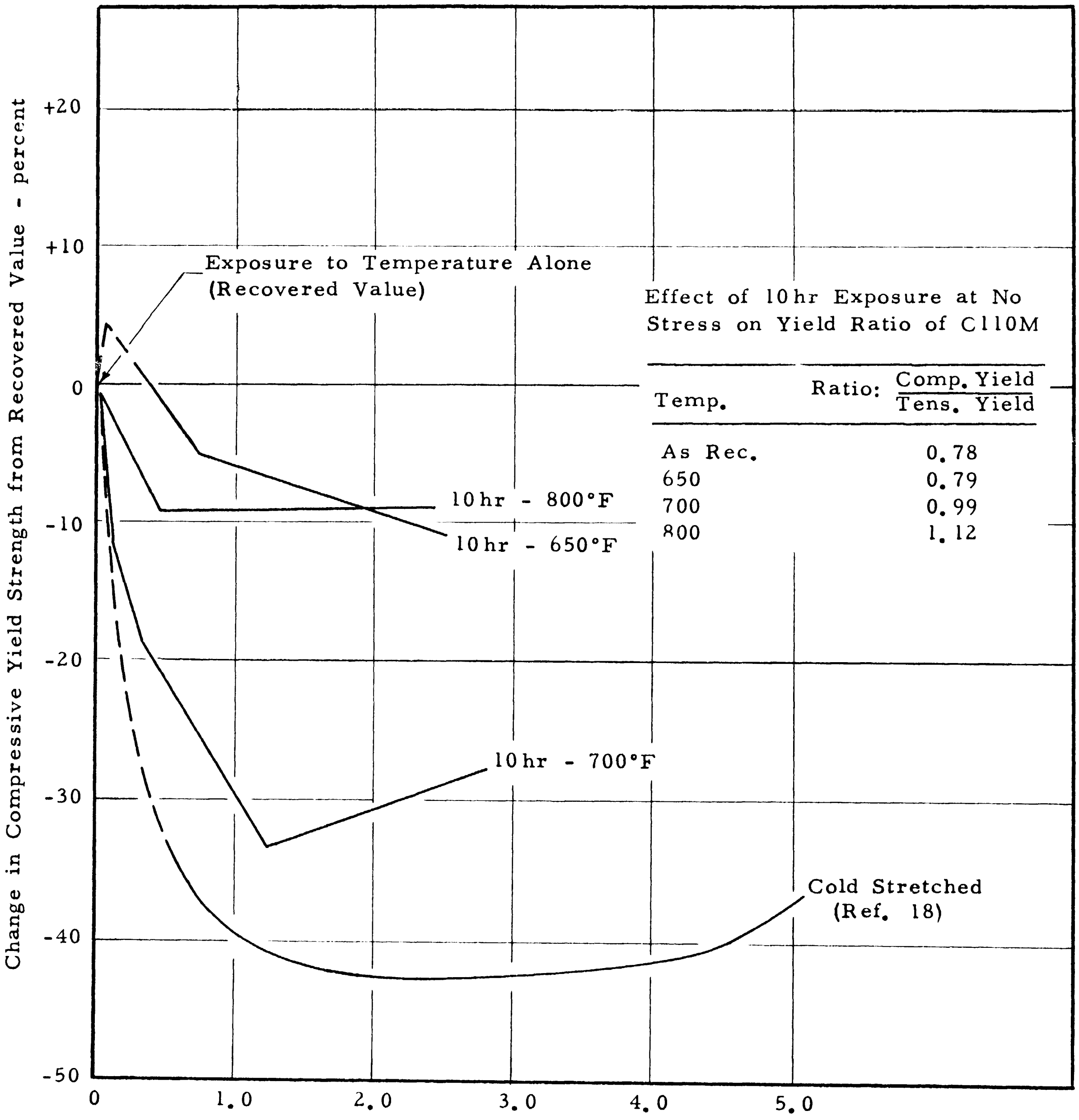


Figure 4. - Effect of 10 hours Creep-Exposure on Relative Compressive Yield Strength of C110M (Ti-8 Mn)

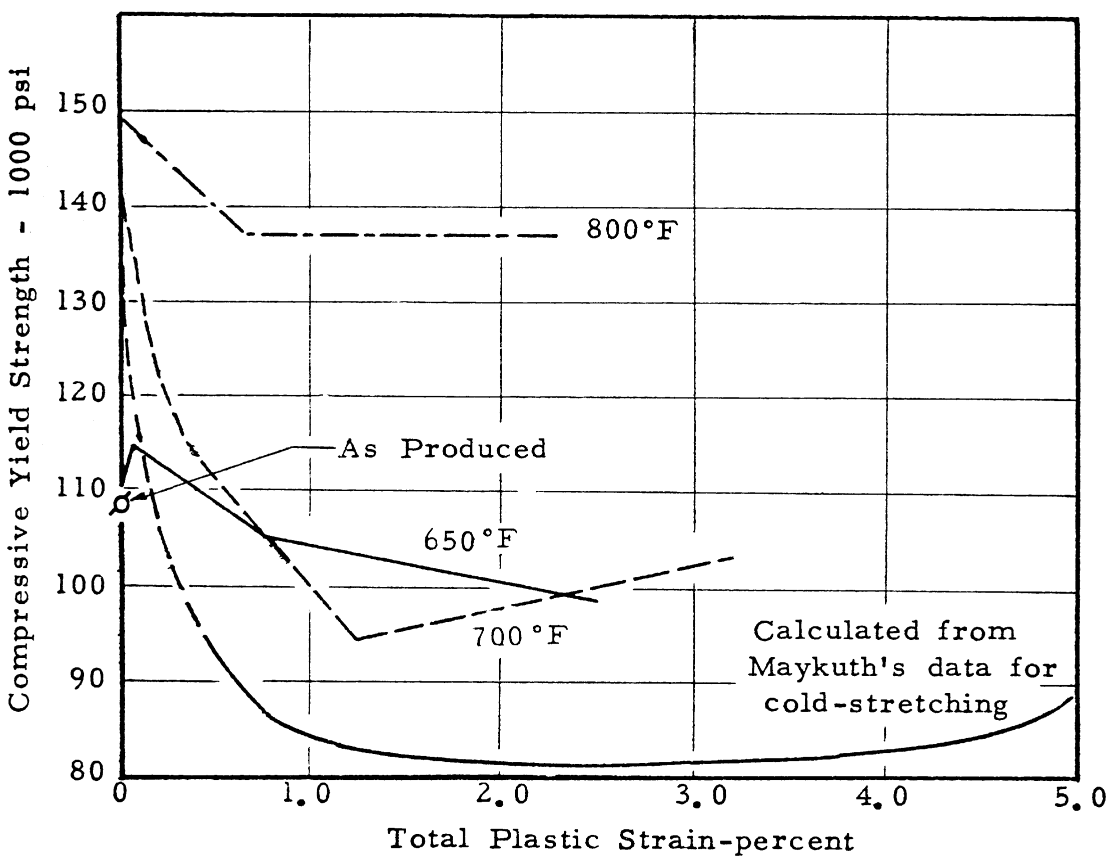


Figure 5. - Effect of 10-hours Creep Exposure on Compressive Yield Strength of C110M.

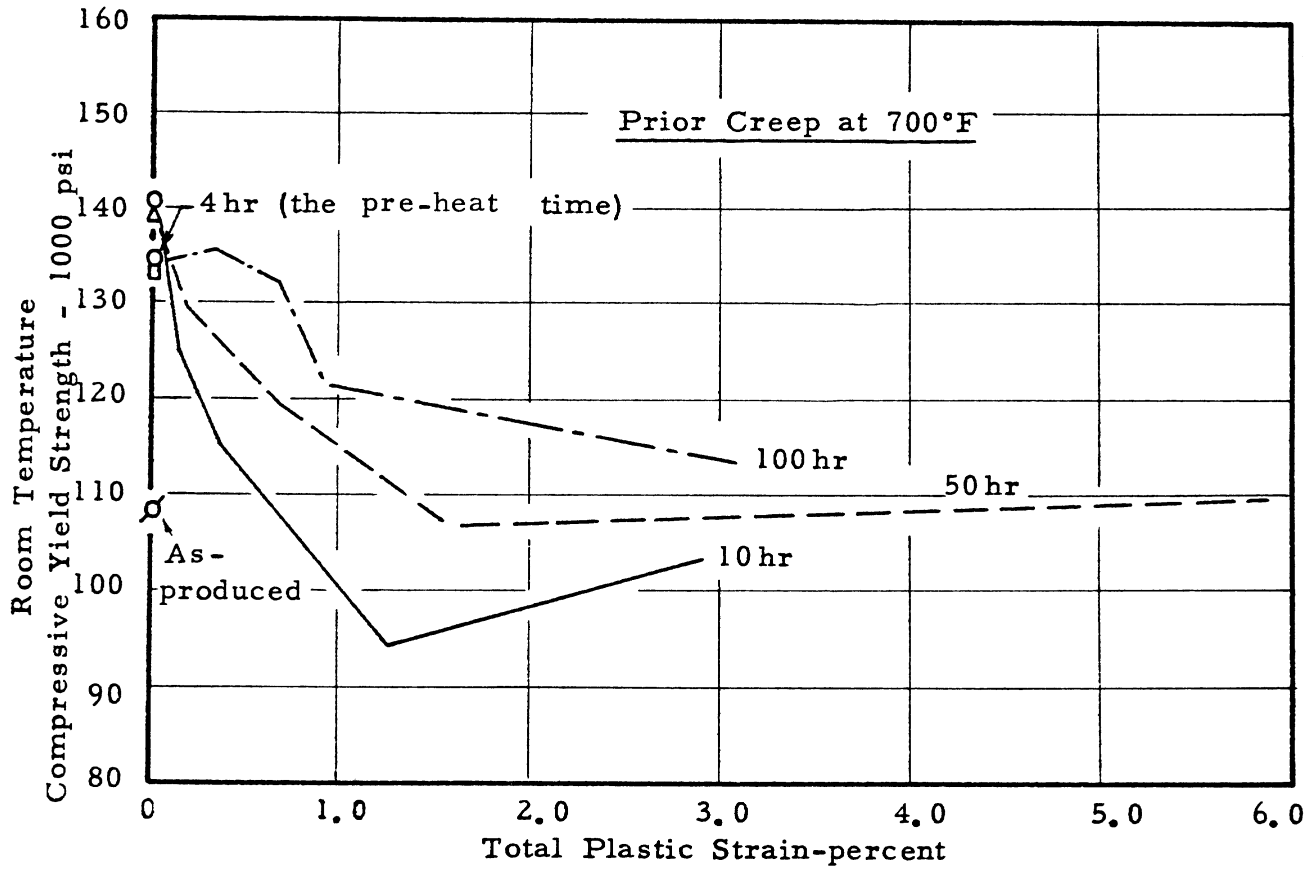


Figure 6. - Effect of Prior Creep Time and Total Strain at 700°F on Room Temperature Compressive Yield Strength of C110M.

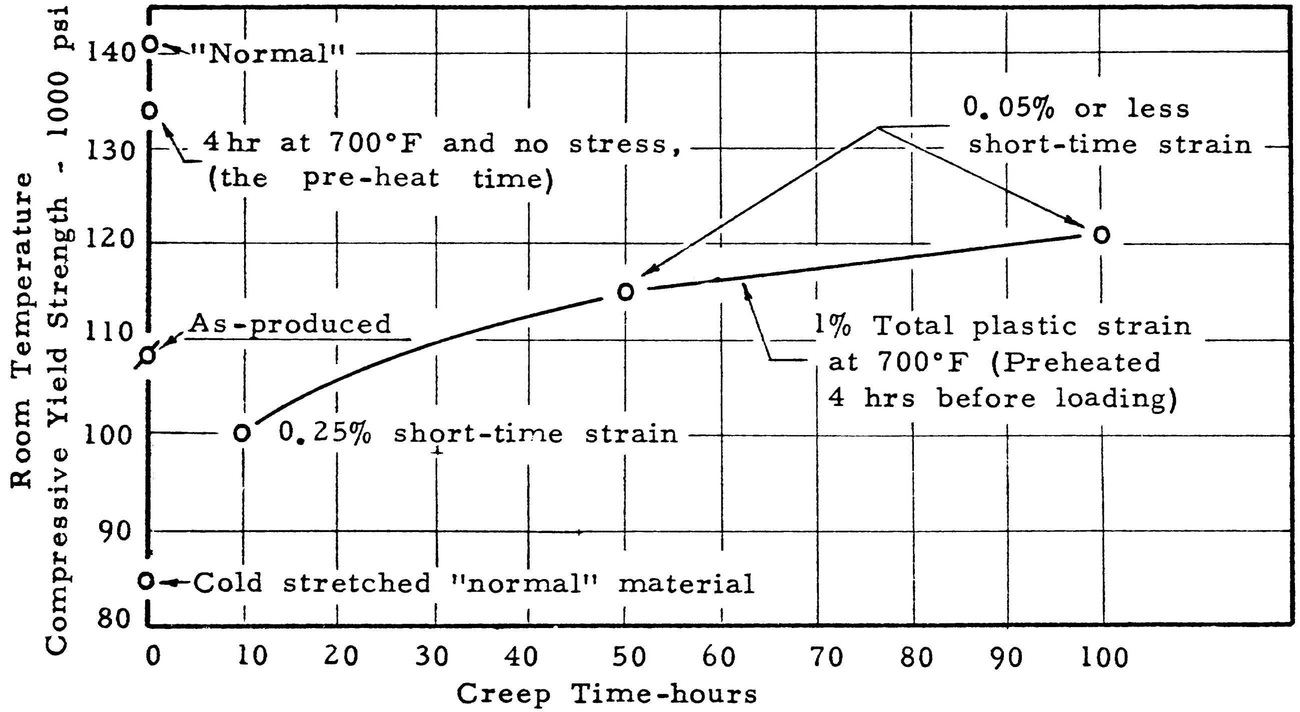


Figure 7. - Effect of Exposure Time to Reach 1-Percent Total Plastic Strain at 700°F on Room Temperature Compressive Yield Strength of C110M.

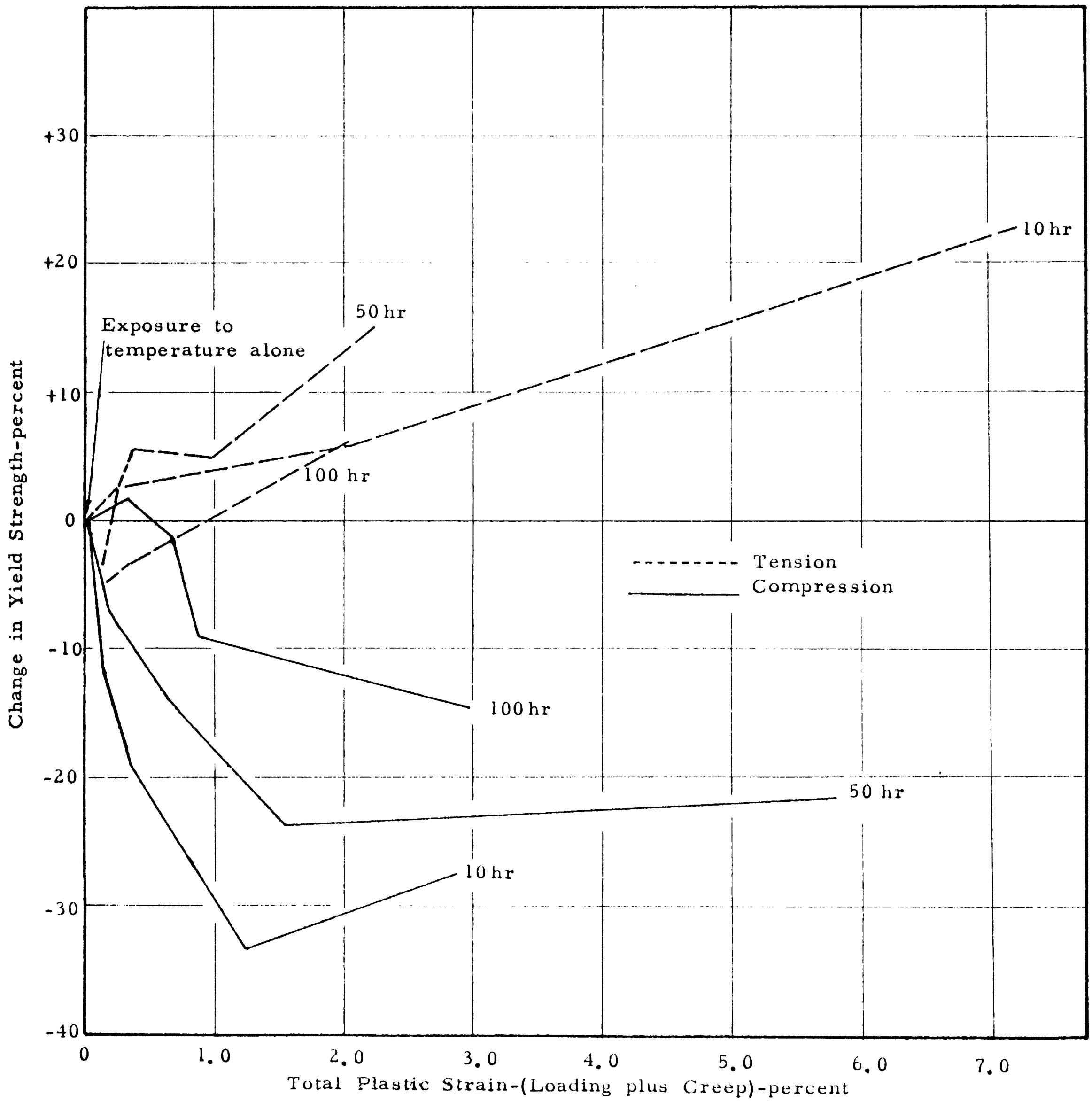


Figure 8. Percent Change in Yield Strength of C110M From 10, 50, or 100-Hour Creep-Exposure at 700°F.

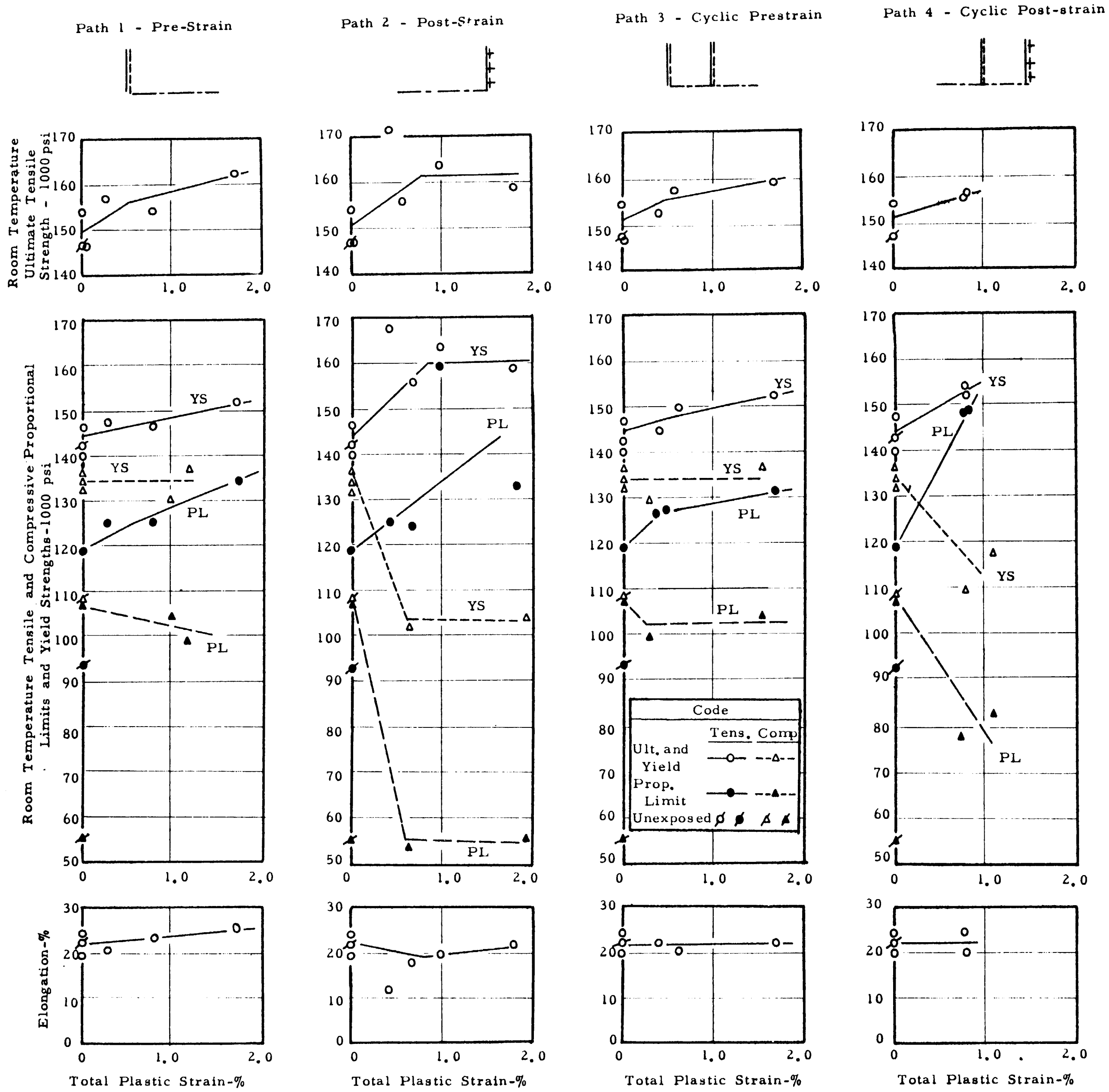


Figure 9. - Effect of Short-Time Strain Paths on Room Temperature Properties of C110M Exposed 100-hours at 700°F.

100 hours at 700°F

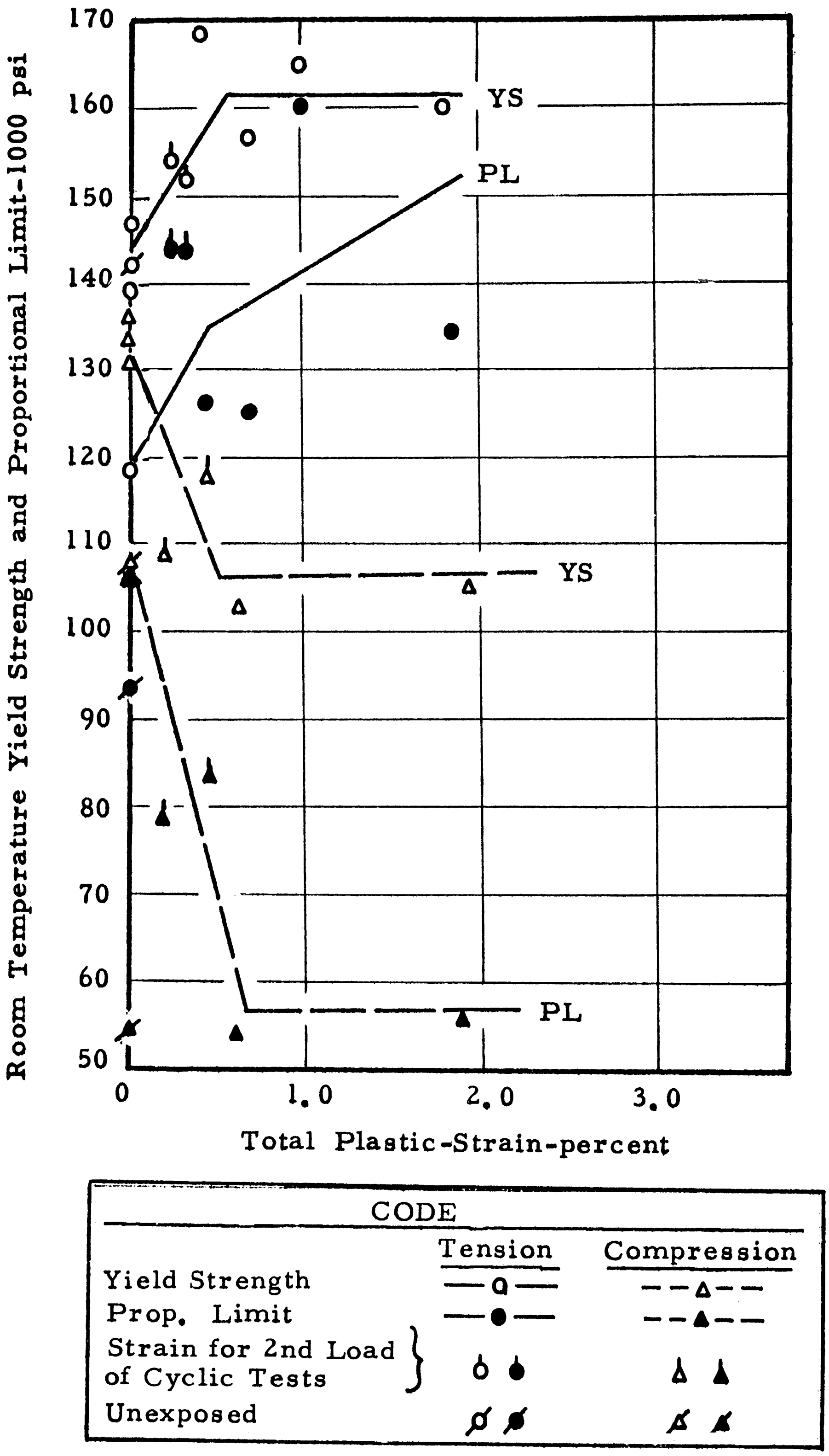


Figure 10. - Effect of Post-Strain (Path 2) and 2nd Loading of Cyclic Post-Strain (Path 4) on Room Temperature Yield Strength and Proportional Limit of C110M Exposed 100-hrs at 700°F.

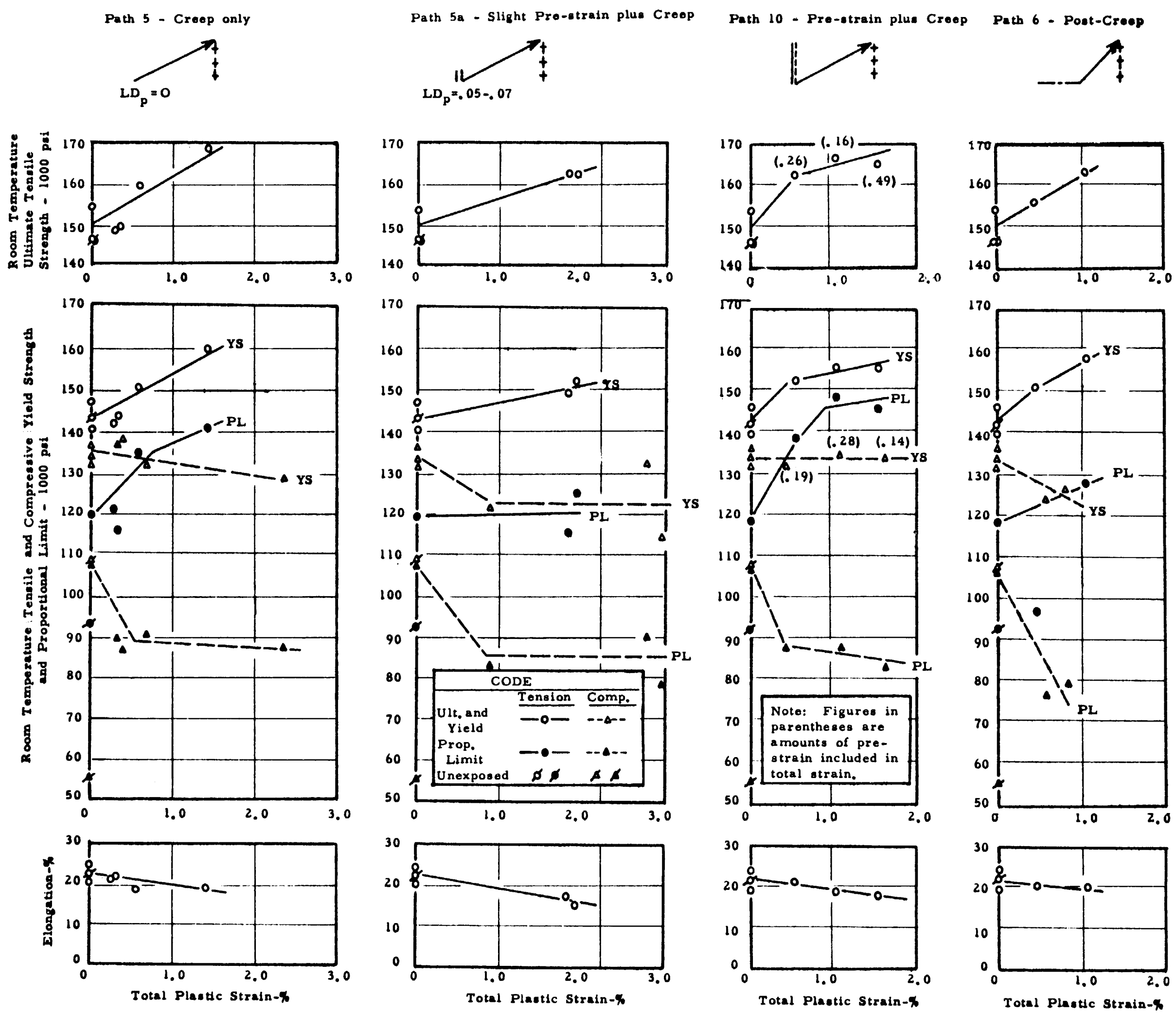


Figure 11. - Effect of Variable Creep Paths on Room Temperature Tension and Compression Properties of C110M Exposed 100-hours at 700°F.

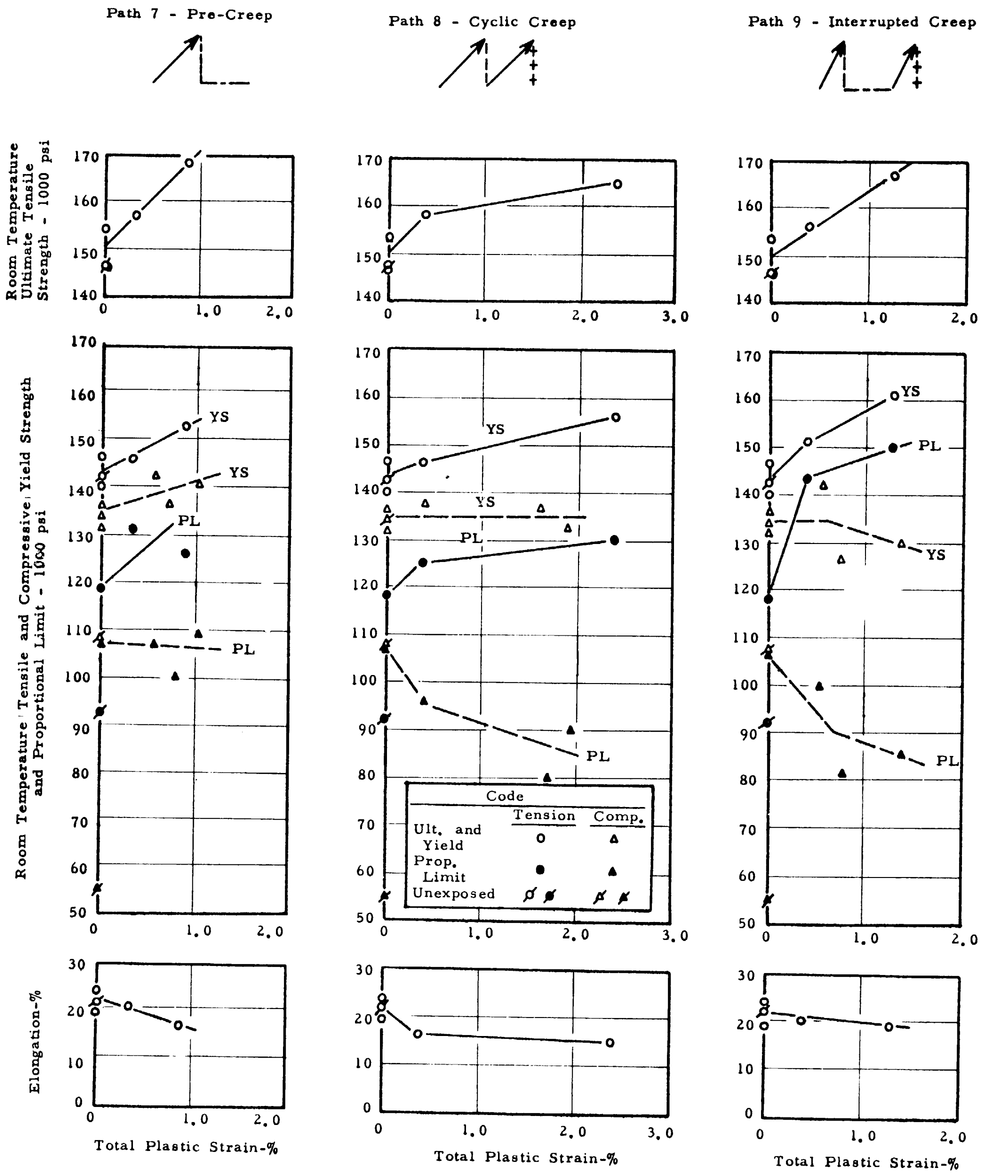


Figure 11. (Continued) - Effect of Variable Creep Paths on Room Temperature Tension and Compression Properties of C110M Exposed 100-hours at 700°F.

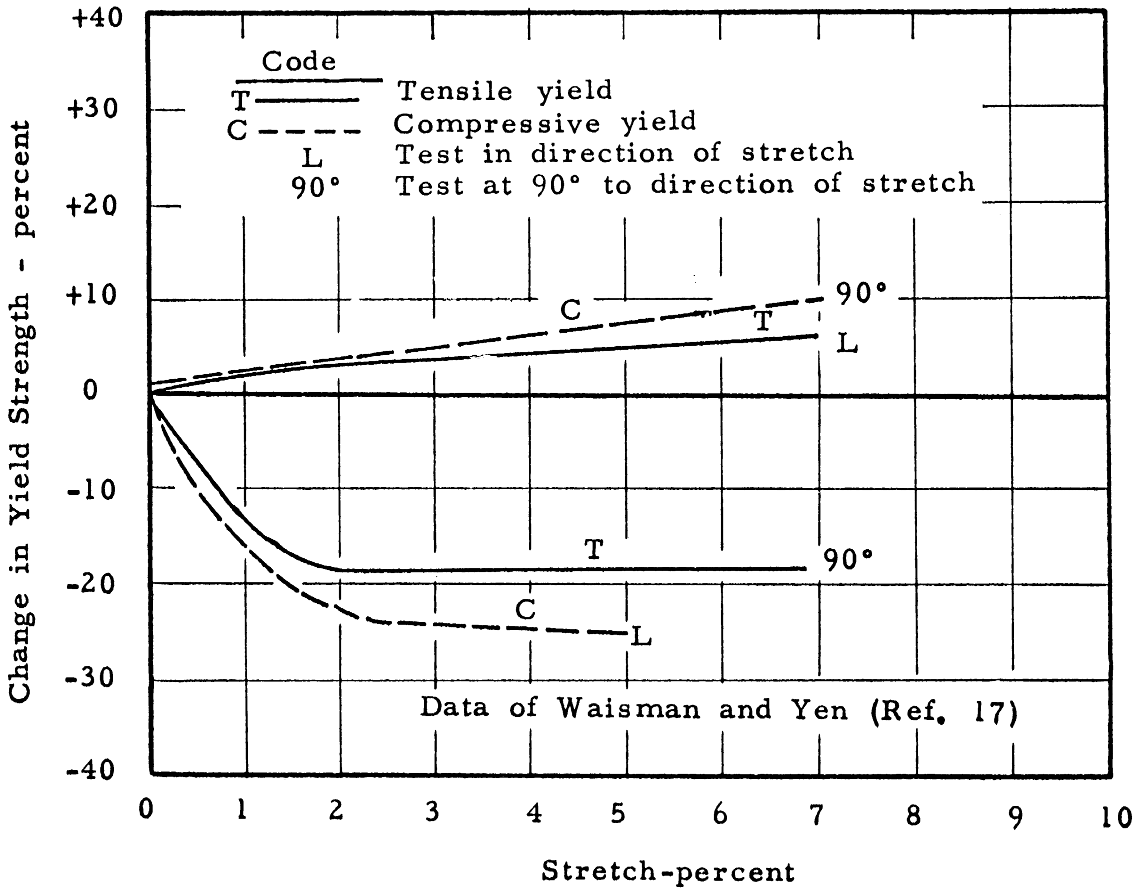


Figure 12. - Effect of Stretching on Tensile and Compressive Yield Strengths of Commercially Pure Titanium at 0° and 90° to the Stretching Direction (Ref. 17).

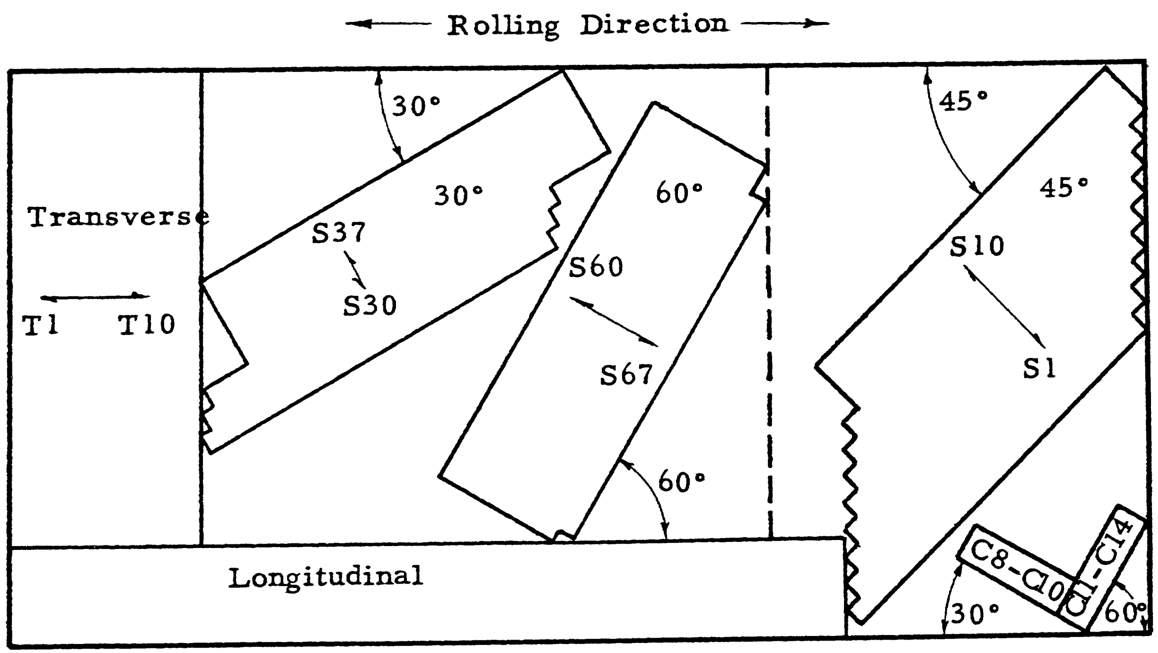


Figure 13. - Cutting Pattern and Identification Code for Orientation Studies of C110M Titanium.

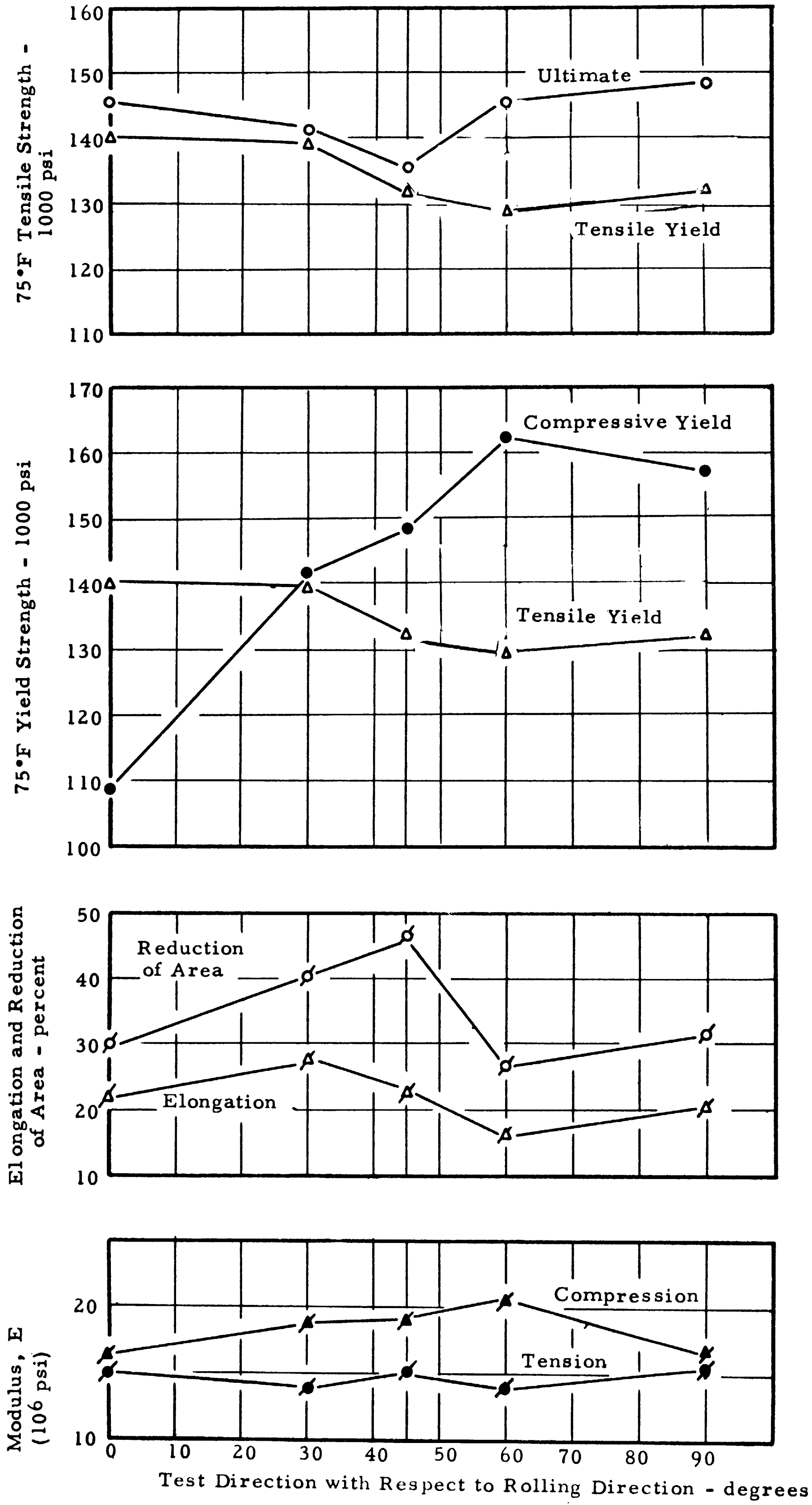


Figure 14. - Effect of Specimen Orientation with Respect to Sheet Rolling Direction on Room Temperature Mechanical Properties of C110M.

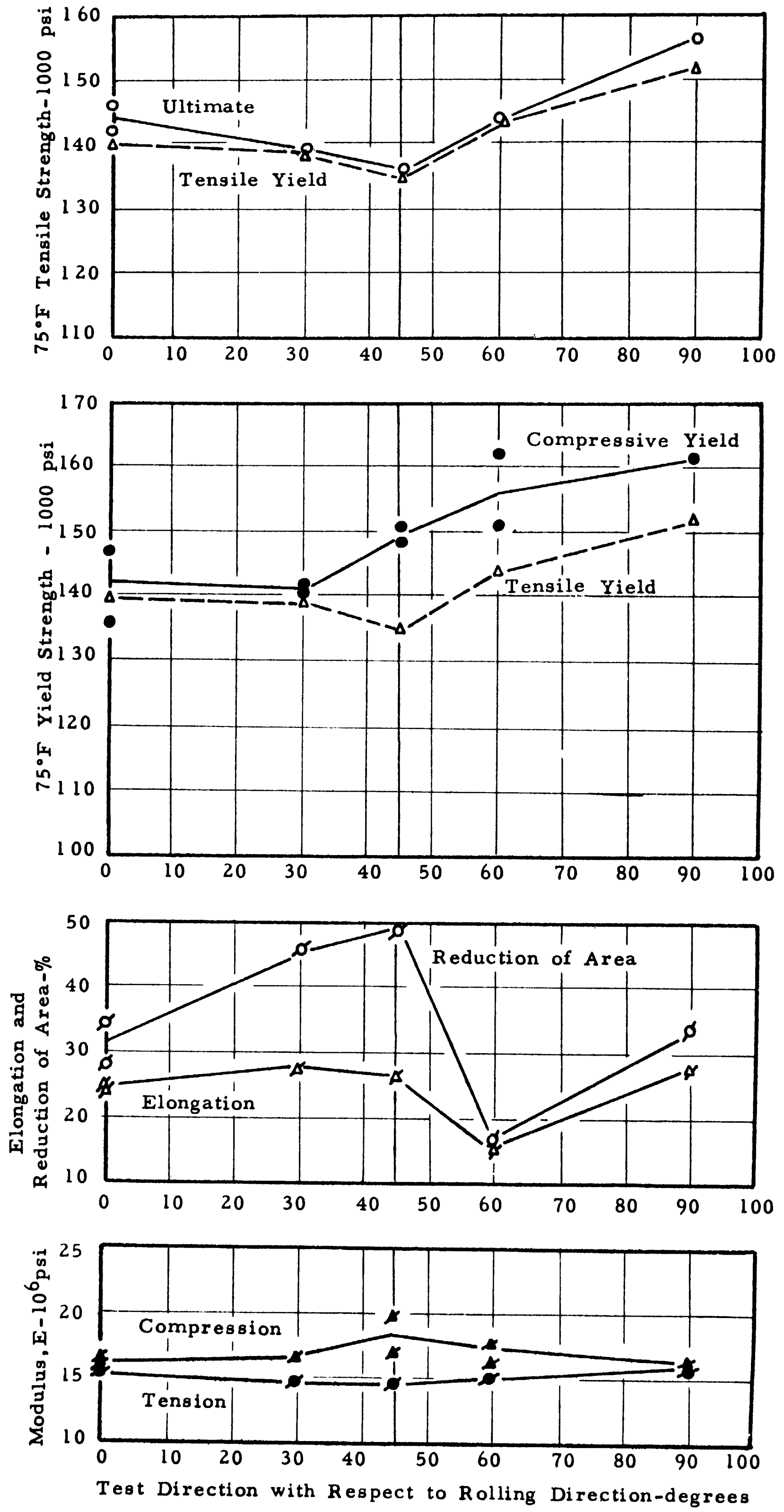
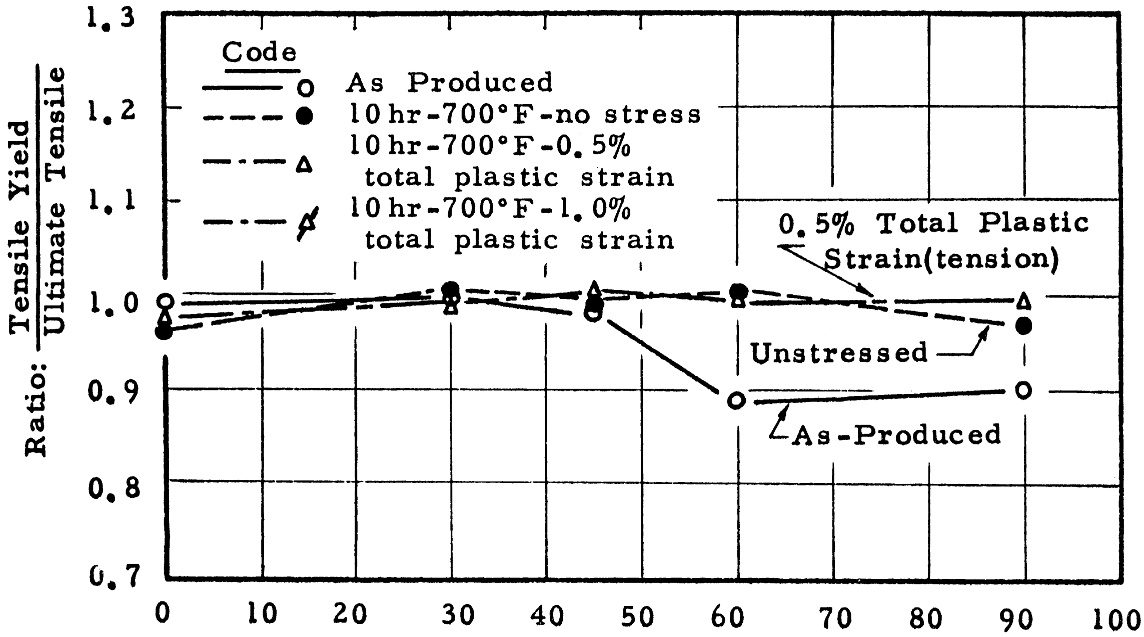


Figure 15. - Effect of 10-hours Unstressed Exposure at 700°F on Room Temperature Mechanical Properties of C110M Titanium at Various Orientations with Respect to the Sheet Rolling Direction.



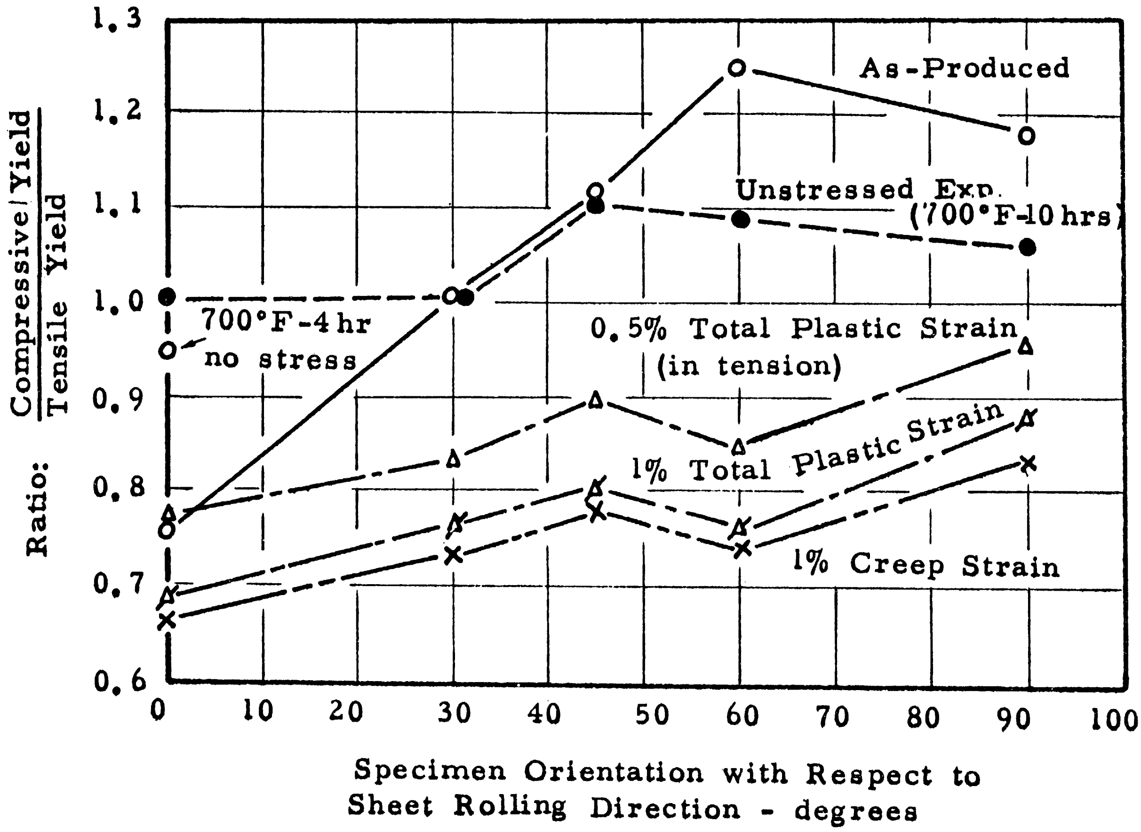


Figure 16. - Effect of Exposure Conditions on Yield and Tensile Ratios of C110M Titanium.

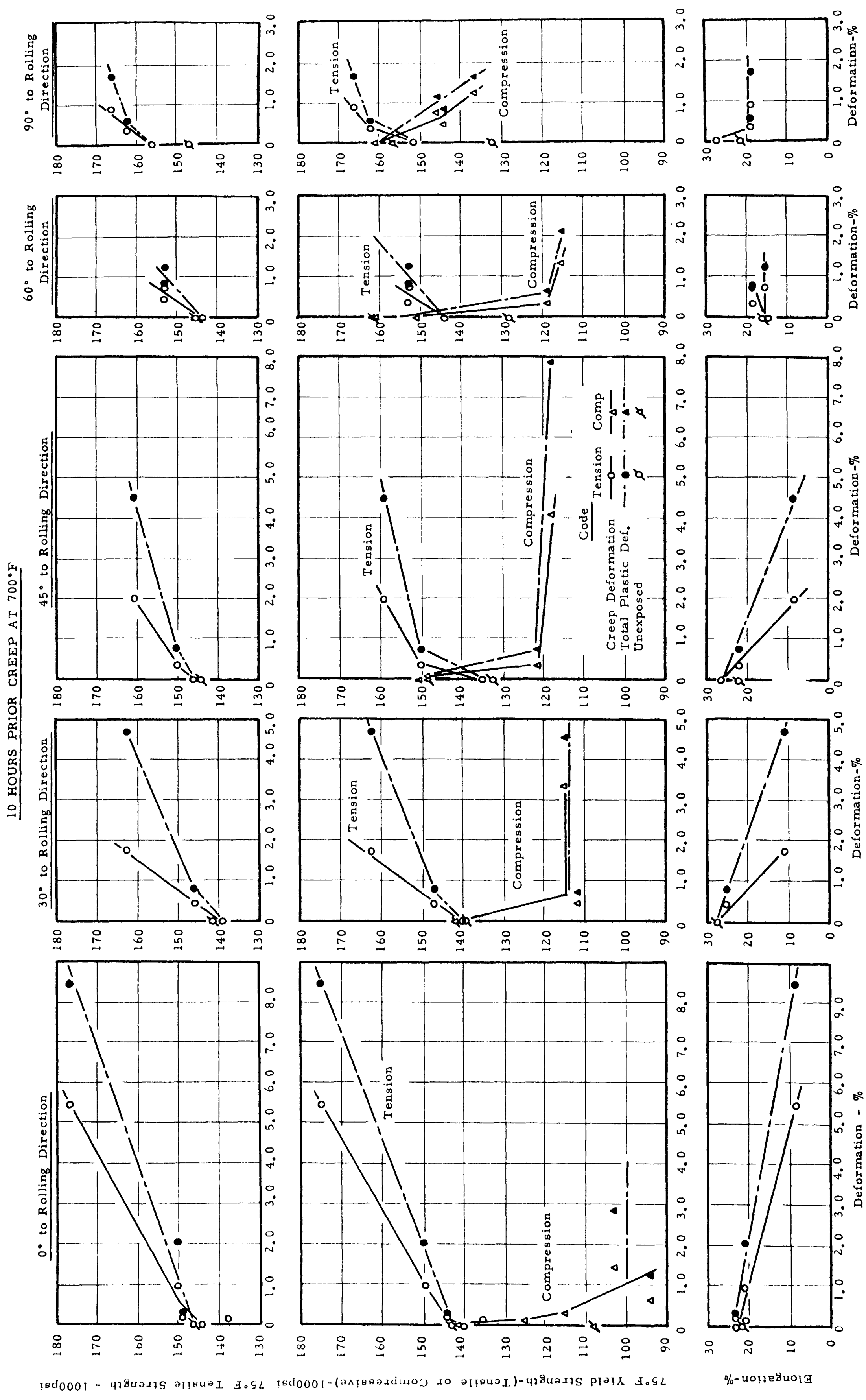


Figure 17. - Effect of Specimen Orientation with Respect to Sheet Rolling Direction on Room Temperature Mechanical Properties of C110M After 10 Hours Prior Creep Exposure at 700°F.

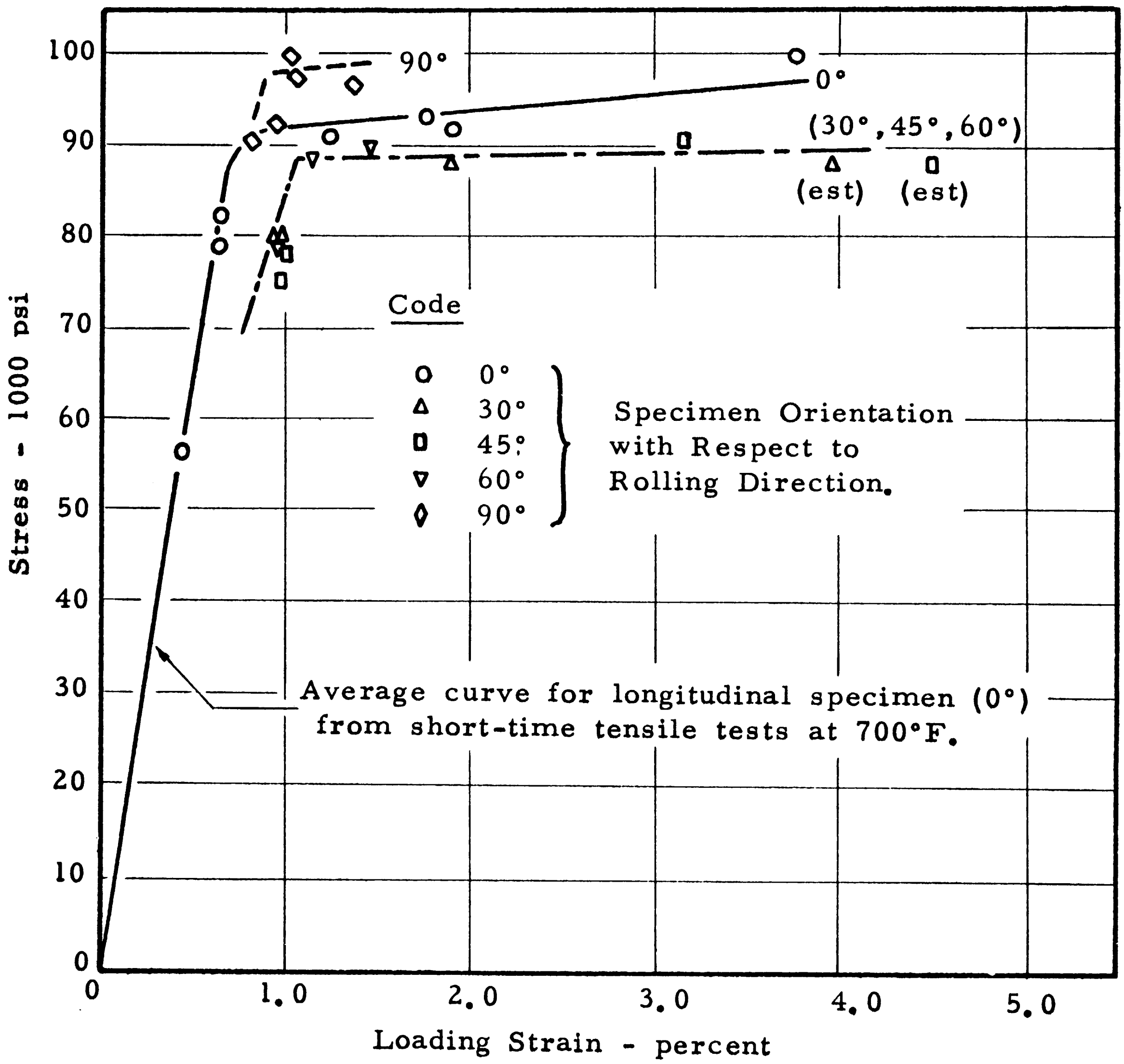


Figure 18. - Effect of Specimen Orientation on Loading Deformation of C110M at 700°F.

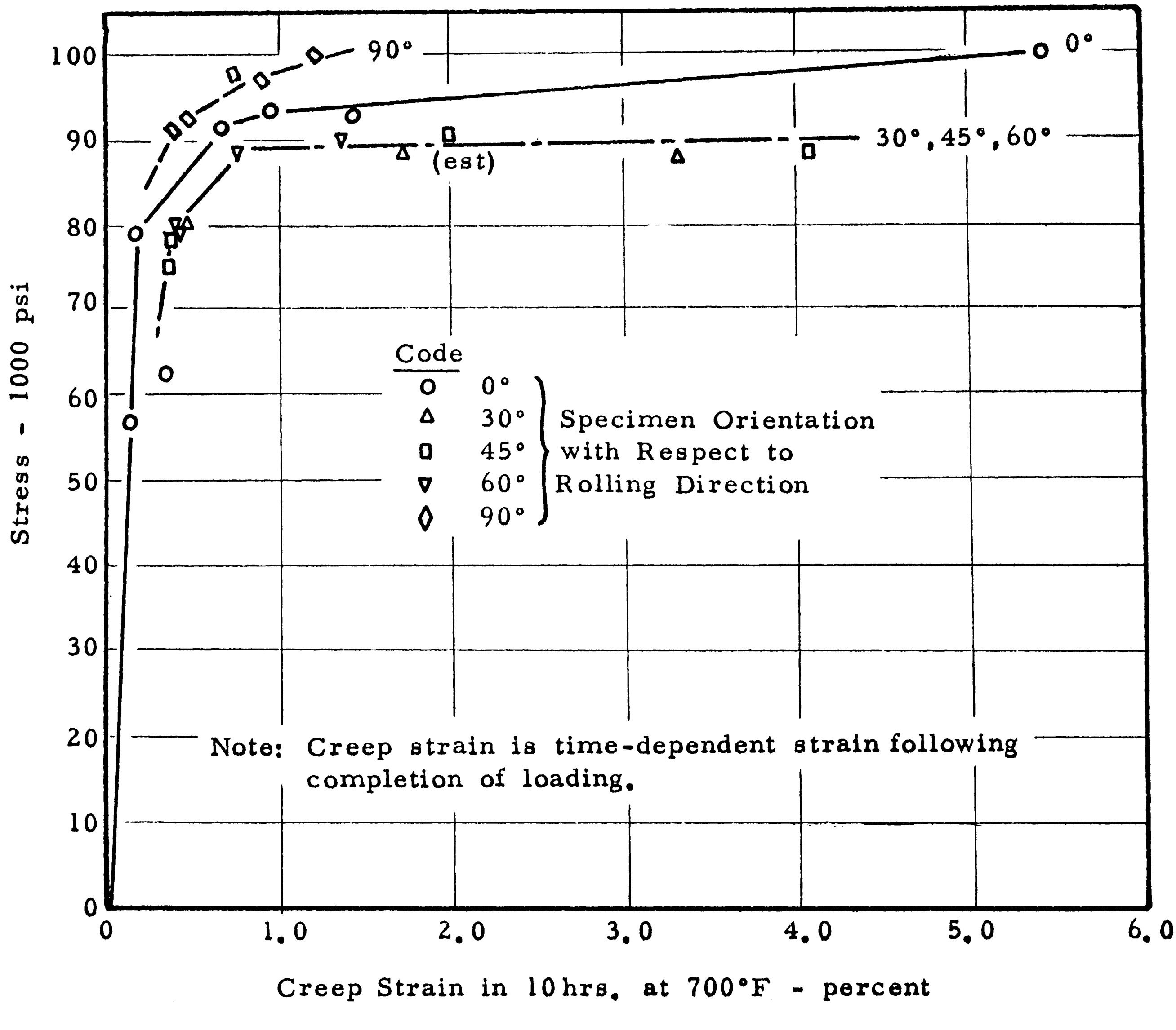


Figure 19. - Effect of Specimen Orientation on Creep Strain Reached in 10 hours for C110M Creep Tested at 700°F.

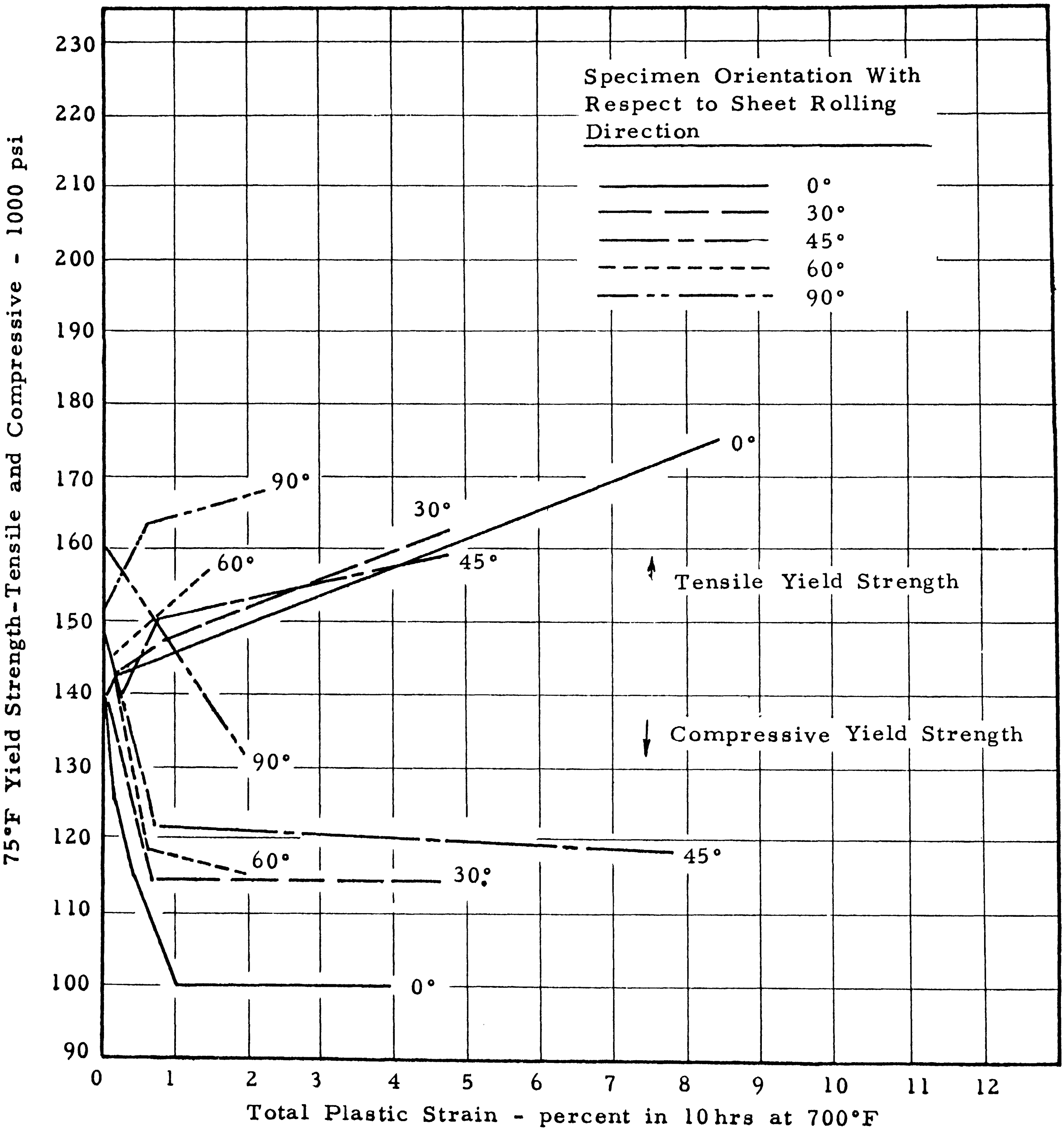


Figure 20. - Effect of 10-hrs Exposure to Stress at 700°F on Tensile and Compressive Yield Strengths of C110M Taken at Various Orientations with Respect to Sheet Rolling Direction.

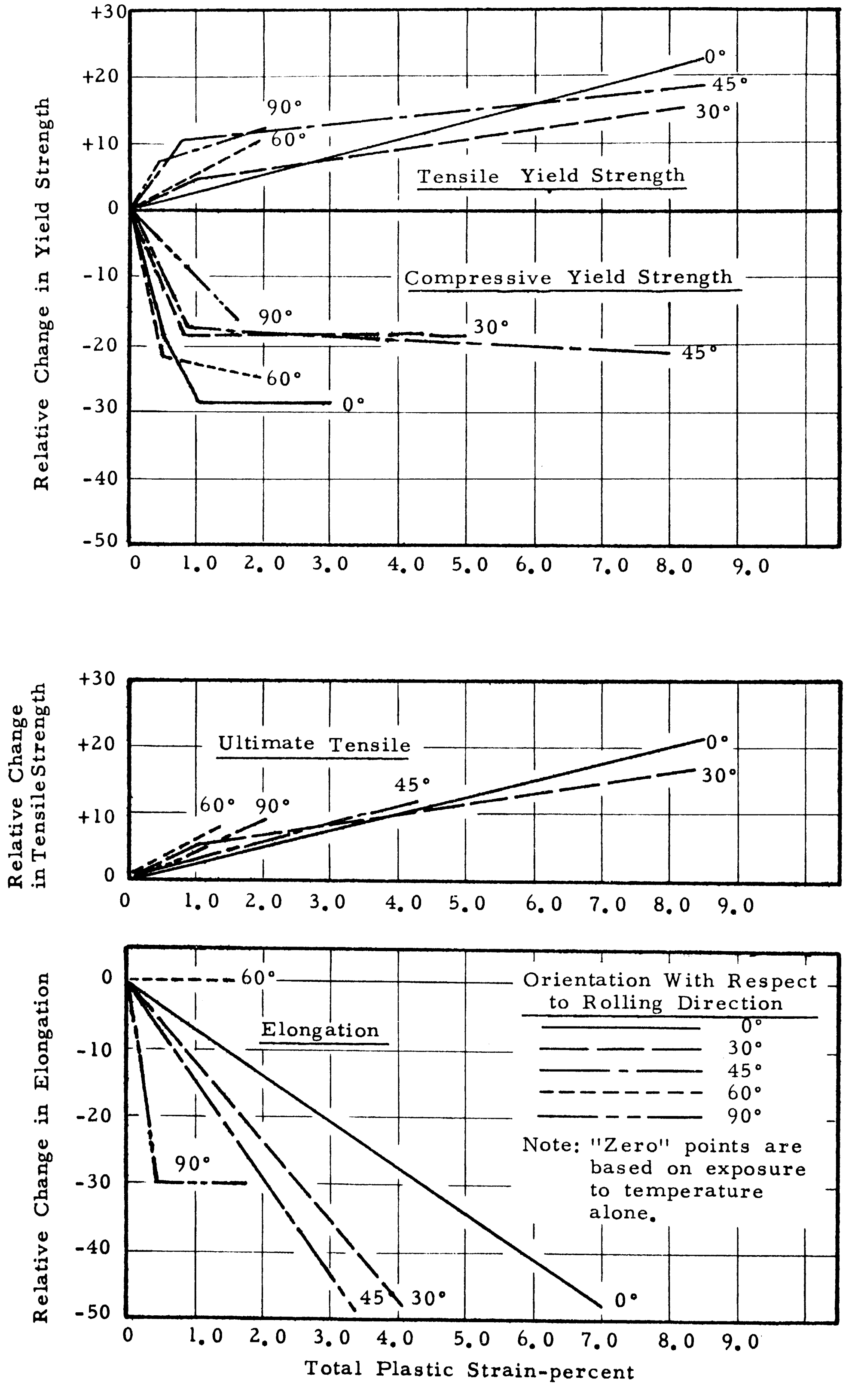
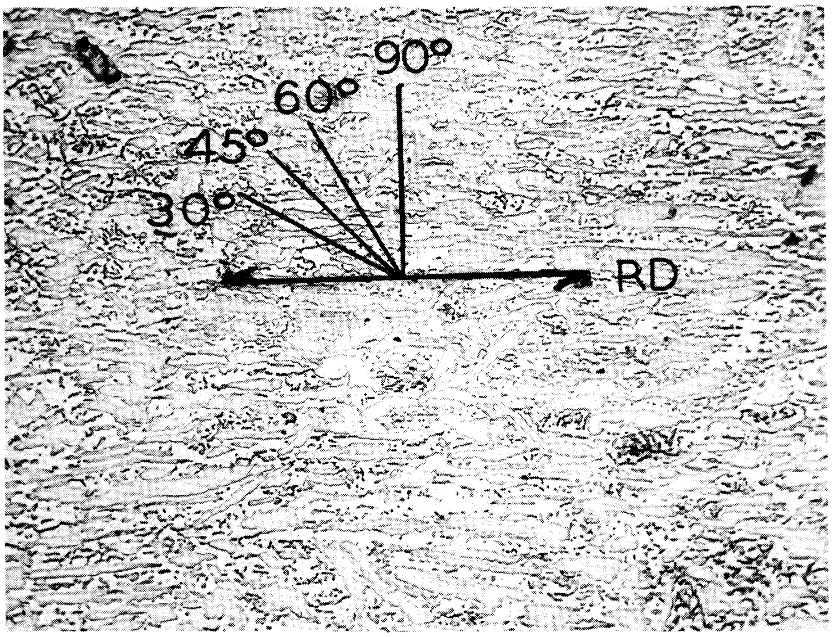
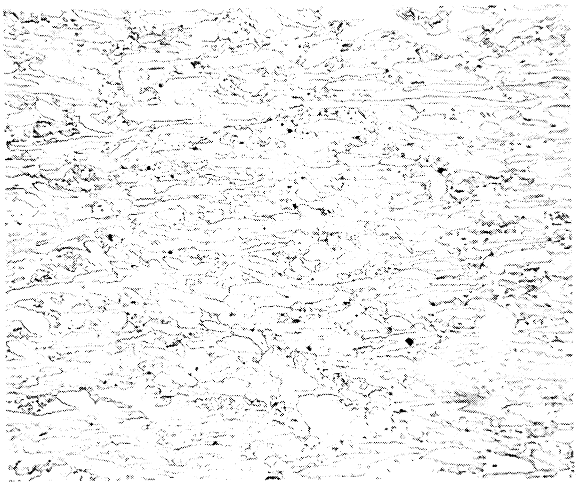


Figure 21. - Effect of Plastic Deformation on Percentage Change in Room Temperature Mechanical Properties Following 10-hours Creep. Exposure at 700°F.

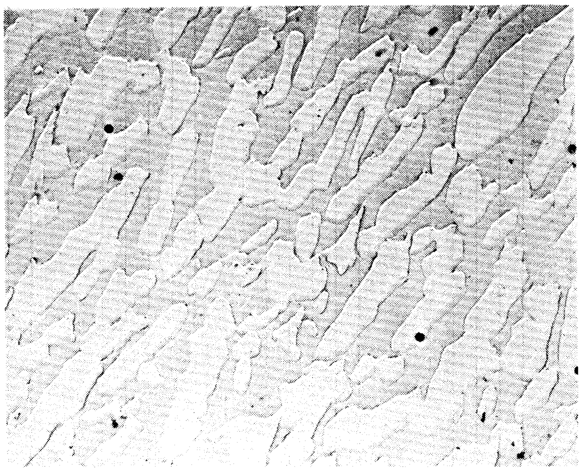


x500 Etchant: lHF, l Gly.

Figure 22. - C110M As Produced-Longitudinal Surface - Test Directions Indicated With Respect to Sheet Rolling Direction.



C110M 500x
As-Produced
(Optical Micrograph)



C110M 3500x
As-Produced
(Electron Micrograph)

Figure 23. - Optical and Electron Micrographs of C110M As-Produced (Transverse Sections).

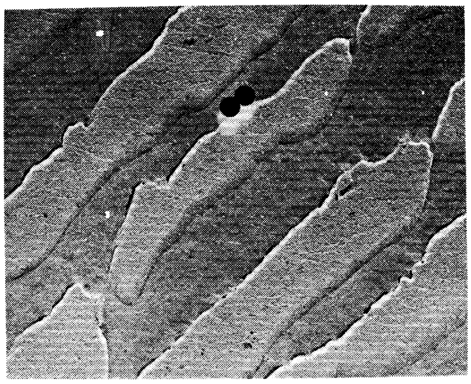


Figure 24 x8200
As Produced

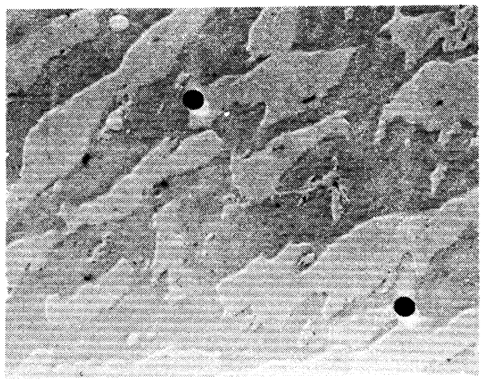


Figure 25 x8200
Creep Test: 650°F-100 hours-
0.40% def.

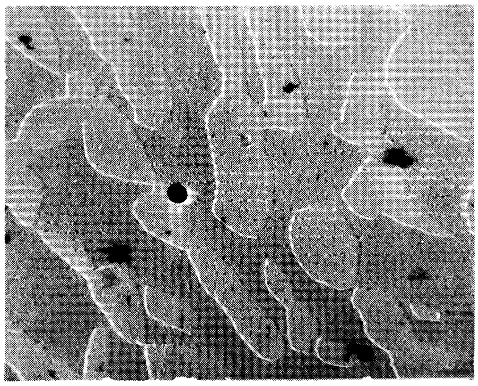


Figure 26 x8200
Exposure Test: 700°F-10 hours-
No stress

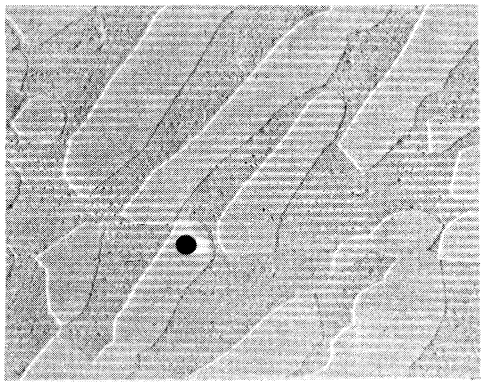


Figure 27 x 8200
Creep Test: 700°F-10 hours-
8.44% def.

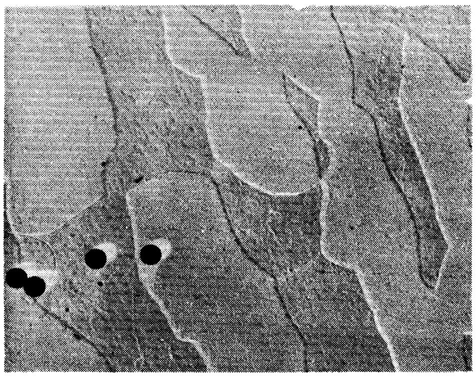


Figure 28 x8200
Exposure Test: 700°F-100 hours-
No stress

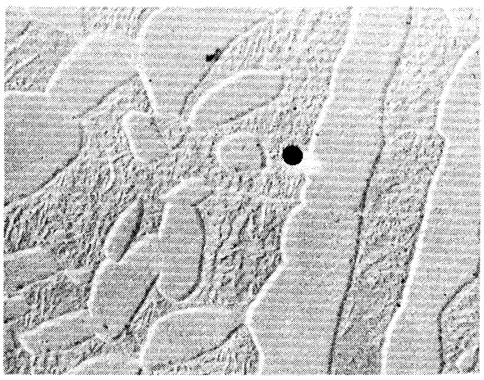


Figure 29 x8200
Creep Test: 700°F-100 hours-
1.81% def.

Note: Deformations are total plastic deformation in indicated creep-exposure.

Figures 24-29. - Electron Micrographs of C110M Titanium (Transverse Sections).

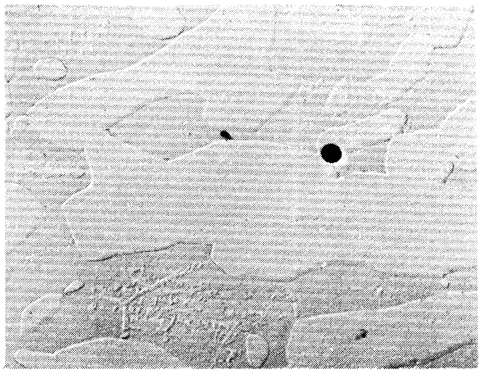


Figure 30 x8200

Exposure Test: 800°F-10 hours-No stress

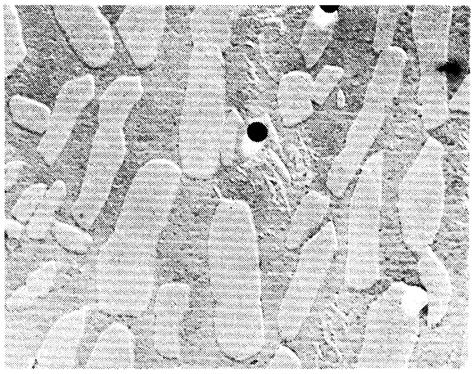


Figure 31 x8200

Creep Test: 800°F-10 hours-0.33% def.

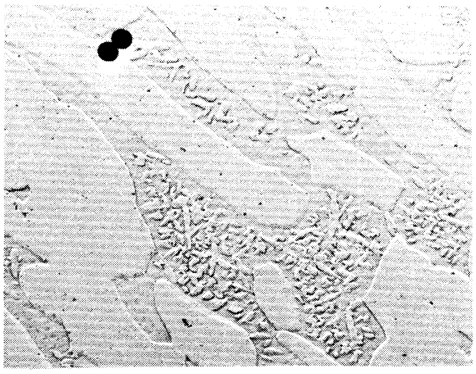


Figure 32 x8200

Exposure Test: 800°F-100 hours-No stress

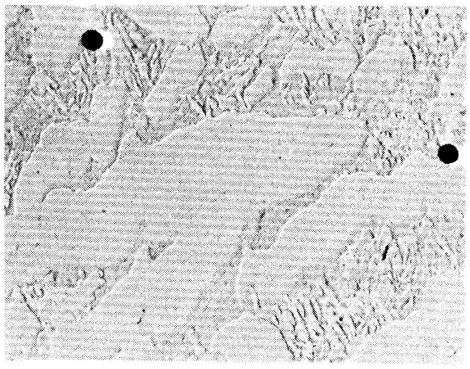


Figure 33 x8200

Creep Test: 800°F-100 hours-2.67% def.

Note: Deformations are total plastic deformations in indicated creep-exposure.

Figures 30-33. - Electron Micrographs of C110M Titanium (Transverse Section).

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